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Crater measurements from approximately 1000 feet more than 100 miles with charge weights ranging from less than 100 to 10,000 lb were analyzed to: (a) obtain whether variations in the problems involved in determining the shape and size of craters formed by high explosives; (b) establish the order of variation that characterizes cratering; and (c) develop improved and more general cratering techniques for predicting crater dimensions. Existing data for craters fired in water and on the ground were determined, and plots of crater radius and depth as a function of charge weight. By means of the least-squares procedure, the equation of the line best fitting the data was determined, along with 95% confidence limits, thereby establishing empirically the scaling laws that relate crater size and charge weight. The well-known cube-root scaling law is not

Crater measurements from approximately 1000 shots in more than 20 wells with charge weight ranging from less than 1 lb to 30,000 lb were analyzed to: (a) gain a better understanding of the problems involved in determining the shape and size of craters formed by high explosives; (b) establish the order of variation that characterizes cratering laws; and (c) develop improved and/or more generalized techniques for predicting crater dimensions. Scaling trends for shots fired on or under the ground were determined from plots of crater radius and depth as a function of charge weight. By means of the least-squares procedure, the equation of the line best fitting the data was determined, along with 95% confidence limits, thereby establishing empirically the scaling laws that relate crater size and charge weight. The well-known cube-root scaling law is not

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Crater measurements from approximately 1,300 shots in more than 20 wells with charge weights ranging from less than 1 lb to 350,000 lb were analyzed to: (a) gain a better understanding of the problems involved in determining the shape and size of craters formed by high explosives; (b) establish the order of variation that characterizes cratering data; and (c) develop improved and/or more generalized techniques for predicting crater dimensions. Scaling plots of shots fired on or under the ground were determined from plots of crater-radius and depth as a function of charge weight. By means of the least-squares procedure, the quantity of the fire best fitting the data was determined, along with 95% confidence limits, thereby establishing empirically the scaling laws that relate crater size and charge weight. The well-known cube-root scaling law is not

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CRATERING FROM HIGH EXPLOSIVE CHARGES

ANALYSIS OF CRATER DATA



TECHNICAL REPORT NO. 2-547

Report 2

June 1961

U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS

Vicksburg, Mississippi

ARMY-MRC VICKSBURG, MISS.

PREFACE

This report is the second and final report on the general subject, cratering from high explosive charges. Presented herein is an empirical analysis of all the HE cratering data compiled in the first report, Compendium of Crater Data.

The study was conducted for the Office, Chief of Engineers, Department of the Army, as a part of Research and Development Project 8S12-95-002, "Nuclear Weapons Effects on Structures, Terrain, and Waterways (U)." It was accomplished during the period July 1959 through June 1960 by personnel of the Special Investigations Section, Hydraulics Division, U. S. Army Engineer Waterways Experiment Station, under the general supervision of Messrs. E. P. Fortson, Jr., and F. R. Brown. This report was prepared by Mr. J. N. Strange, SP-4 C. W. Denzel, and SP-4 T. I. McLane, III, under the direct supervision of Mr. G. L. Arbuthnot, Jr.

Col. Edmund H. Lang, CE, was Director of the Waterways Experiment Station during the preparation of this report, and Mr. J. B. Tiffany was the Technical Director.

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NOTATIONS

- C_s Charge shape factor, dimensionless
- d Depth of crater, ft
- d_a Depth of apparent crater, ft
- d_t Depth of true crater, ft
- D_h Diameter of camouflet (horizontal direction), ft
- D_v Diameter of camouflet (vertical direction), ft
- E_m Elastic properties of medium cratered, lb/ft²
- h Crater lip height, ft
- K Constant, dimensionless
- n Exponent of the charge weight, dimensionless
- r Radius of crater, ft
- r_a Radius of apparent crater, ft
- r_c Radius of explosive charge, ft
- r_t Radius of true crater, ft
- S Soil resistance function dependent upon soil type, dimensionless
- V Volume of crater, ft³
- V_d Detonation velocity of explosive, ft/sec
- W Weight of charge (TNT equivalent), lb
- Z Position of charge above (+) or below (-) air-ground interface, ft

- γ Specific weight of explosive, lb/ft³
- e_p Energy density of explosive (ft-lb/ft³), lb/ft²
- λ_c Reduced charge position ($Z/W^{1/3}$), ft/lb^{1/3}
- μ Poisson's ratio of the medium cratered, dimensionless
- μ_c Moisture content of medium cratered, per cent by weight, dimensionless
- v_m Void ratio of medium cratered, dimensionless
- ρ_c Casting or packing density of the charge, lb-sec²/ft⁴
- ρ_m Density of medium cratered, lb-sec²/ft⁴
- σ_m Strength properties of medium cratered (compression, shear, and tension), lb/ft²

SUMMARY

Crater measurements from approximately 1800 shots in more than 20 media with charge weights ranging from less than 1 lb to 320,000 lb were analyzed to: (a) gain a better understanding of the problems involved in determining the shape and size of craters formed by high explosives; (b) establish the order of variation that characterizes cratering data; and (c) develop improved and/or more generalized techniques for predicting crater dimensions. Scaling trends for shots fired on or under the ground were determined from plots of crater radius and depth as a function of charge weight. By means of the least-squares procedure, the equation of the line best fitting the data was determined, along with 95% confidence limits, thereby establishing empirically the scaling laws that relate crater size and charge weight. The well-known cube-root scaling law is not entirely acceptable for scaling all dimensions of a crater; apparently this law varies with the type of medium being cratered and the charge weight and position. Curves are presented to assist in predicting crater size and shape for charges up to 1,000,000 lb of TNT. Also, the influence of various soil types on crater size is shown graphically.

CRATERING FROM HIGH EXPLOSIVE CHARGES

ANALYSIS OF CRATER DATA

PART I: INTRODUCTION

1. For many years, low energy-density explosives have been used in construction operations to accomplish large excavation projects by loosening or fragmentizing the earth's crust. Equally important is their extensive use in mining operations. Only recently have explosives been used in very large amounts to both loosen and remove unwanted or waste materials. The use of hundreds of thousands and even millions of pounds of explosives to excavate large volumes of materials is daily becoming more commonplace. However, commercial blasting operations usually employ special techniques of delayed initiation and programmed firing of a number of carefully located charges pre-positioned at prescribed depths. Because of the special methods employed, commercial blasting operations normally provide very little information that is usable in predicting the size of crater that a given quantity of high explosive (HE) will produce, and certainly, it is the crater formed by the detonation of single charges that is of major military interest.

2. The importance of cratering was greatly increased when, through the use of nuclear weapons, it became possible to release enormous amounts of energy from essentially a point source. With the coming of the nuclear weapon came also the requirement that prospective users understand fully its potential and its limitations. Naturally, the most certain way to realize a complete understanding of each weapon's effects is from repeated tests at full scale, in which sufficient measurements are made to define each effect. Although this method is preferable from the point of view of accurately establishing weapon effects, it is economically (and perhaps biologically, because of the radioactive fallout) infeasible; therefore, efforts have been made to establish and define many of the full-scale effects by use of small-scale HE charges. Cratering is one of the effects of nuclear weapons that has been studied using HE charges.

3. Over a period of the last twenty or so years, many HE cratering experiments have been conducted in an effort to determine the cratering

capability of various explosives. Primarily the cratering phenomena have been considered to be a function of (a) the depth of burial of charge, (b) the properties of the medium in which the charge is placed, (c) the type of explosive, and (d) the weight of the charge. Most treatments of the subject of cratering have made use of data obtained in a specific test series. As a result, few collations among various test series were attempted. When comparisons were attempted and found to be widely divergent, justifications were sought as to why one test series should be used in preference to another. Such practices in some instances greatly reduced scatter and/or served to bias the conclusions reached.

4. It seemed appropriate therefore that a study should be initiated in which (a) all known cratering data would be tabulated along with pertinent soil properties, explosive types, and charge weights and depths of burial; and (b) the data so compiled would be analyzed as thoroughly as practicable. The study undertaken was divided into two phases, viz., compilation of crater data, and analysis of crater data. The report on the first phase entitled Compendium of Crater Data, was published as Report 1 of this series in May 1960.^{7*} The major objectives of this, the second phase of the study, were to (a) obtain a better understanding of the cratering process, (b) assess the order of variation (scatter) that characterizes cratering phenomena in specific and widely divergent materials, and (c) develop, if practicable, improved and/or more generalized methods of predicting the size and shape of explosively generated craters for a variety of soil conditions.

5. Since the measurements of explosively generated craters were very often reported merely as by-products of test series planned for other purposes, most of the data tabulated in the compendium are grossly inadequate for a truly scientific approach to a general solution of the cratering problem. Consequently, it was not possible to realize an analysis that fulfilled all of the objectives stated above. Attempts to refine the analysis to include the effects of additional parameters were unsuccessful. Results are presented in as great detail as the "input" data warrant.

* Raised numbers refer to similarly numbered items in the list of references at end of text.

PART II: EXPERIENCE FROM EARLIER INVESTIGATIONS

British Investigations

6. In 1940 the British conducted a series of tests¹ to determine, empirically, equations that would provide means of predicting the size and shape of craters resulting from the detonation of HE charges (bombs) above, on, or beneath the air-ground interface. These tests were conducted within soil and rock masses so chosen as to be generally representative of the land mass of England. From these tests, a set of cratering capability curves* was produced for predicting crater dimensions in a variety of earth media.

7. By the end of 1941 the British had accumulated sufficient data from actual bombings to formulate a second set of empirical equations. These differed somewhat from the first, mainly because of a difference in the methods of emplacing the charge. In the experimental tests much larger cavities were formed than in the actual bombings. In the experimental tests the backfilling materials used in the bomb emplacement were carefully tamped and controlled, whereas in the actual bombings the bomb itself was open to the atmosphere through the penetration burrow. Obviously the energy released by the detonations was partitioned differently between the media and the air.

8. Within the range of charge weights involved, the data, both from actual bombings and from the experimental work, conformed satisfactorily to Hopkinson's law. This law states that if charges of the same explosive, differing in weight but not in shape, are detonated, the explosive effects are proportional to the linear dimensions of the two charges. Thus, a sphere of TNT that has a diameter twice that of a second sphere will, upon detonation produce twice as big a crater and twice as much damage (i.e., the explosive effects will be twice as severe).

* Any plot of a reduced crater dimension versus the reduced charge position; e.g., $d/W^{1/3}$ versus λ_c ; $d/W^{0.3}$ versus λ_c ; $r/W^{1/3}$ versus λ_c ; etc.

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United States Investigations

9. Some experiments were conducted by the United States in 1941 to assess the damage that structures might receive from bombs bursting nearby. The tests showed that, even in the case of buried bombs, it was possible to cause considerable damage to buildings situated near the explosion. From the results it was determined that a broad experimental program would be required to assess the roles of the various test parameters in causing damage. The tests also revealed that underground installations could best be attacked by actual cratering of the soil-structure mass; therefore, the relative influence of the various test parameters on the cratering process became important.

10. These studies were among the first which led to a series of prolonged studies of the cratering problem and the various factors which influence crater formation.

PART III: VARIABLES THAT AFFECT CRATERING PHENOMENA

11. If the cratering problem is generalized, it can be said that the size and shape of an explosively generated crater are dependent upon: the quantity and type of explosive used, the medium in which the cratering takes place, and the method of emplacement of the charge and its position relative to the medium-air interface. These independent variables are very complex and cannot be defined completely or adequately enough to permit a study of the cratering problem in minute detail. Every attempt at analysis is complicated by other variables that are less obvious and by an interrelation of the variables named above. In view of these difficulties, it is very likely that crater-prediction methods will, for some time at least, contain provisional techniques for assessing certain factors which exert considerable influence on the cratering process.

12. The following tabulation lists the more obvious variables that are believed to have significant influence upon the cratering problem. The extent to which other variables might conceivably influence the problem is indeterminable. Because of the quality of the data available, the effects of several of the more obvious variables on crater formation could not be determined in this study.

<u>Properties of Charge</u>	<u>Properties of Medium Being Cratered</u>	<u>Charge Position</u>
Weight	Density	Above-ground regime
Shape	Moisture content	Air-ground interface
Packing or casting density	Dynamic load-deformation characteristics: modulus of elasticity, ultimate strength (compression, tension, and shear), Poisson's ratio, etc.	Below-ground regime
Energy density		
Detonation velocity		
	Void ratio	
	Other soil properties which may produce third- or higher-order effects	

Properties of Explosive Charge

13. Properties of the explosive are of major importance in determining the size crater that a given charge will produce. The weight of explosive, in conjunction with the shape and size of the charge, determines packing density. Ideally, for purposes other than evaluating shaped-charge effects, spherical charges are best suited to experimental tests wherein it is desirable to eliminate the charge shape as a factor in the cratering process and to more nearly simulate a point source of energy. Experience has shown, however, that charges which do not deviate greatly from a cubical shape produce little or no charge-shape effect on the size or shape of the crater formed. Tests have been conducted^{2,3} that were designed specifically to evaluate the effect of charge shape on crater shape and size. However, these tests were for a particular purpose and are not considered pertinent to the general solution of the cratering problem when spherical charges are used.

14. Since cratering involves deformation, displacement, and throwout of the soil mass that has received loads sufficient to exceed the elastic limit of the medium, it is obvious that such effects will increase in magnitude as the charge weight is increased. Experience has shown that for the smaller charges ($W < 1000$ lb), the explosion effects are fairly well predicted by Hopkinson's law (see paragraph 8). Although all explosion effects do not adhere to this law in the absolute sense, it may be used to describe the behavior of the explosion effects in an approximate manner.

15. From certain test results⁷ where comparison is possible, it has been qualitatively determined that explosion effectiveness in producing a crater is a function of the detonation velocity. A "rule of thumb" summation of test results shows that the more effective crater-producing explosives are those having the slower detonation velocities. For example, 60% ammonium dynamite (detonation velocity approximately 9700 ft/sec) is about 30 to 50% more effective than C-4 (detonation velocity about 24,000 ft/sec) in producing a crater when equal amounts of energy are released. Furthermore, explosives having detonation velocities slower than that of ammonium dynamite are even more effective from the standpoint of producing craters. Since the energy density of explosives is directly related to the

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detonation velocity, low energy-density explosives are more efficient cratering charges.

Properties of the Medium Cratered

16. Several properties of the medium being cratered influence to a pronounced degree the size of crater which the detonation of a given amount of explosive can produce. Generally, the earth's crust may be described as being a non-uniform, nonlinear, randomly constituted mass that makes up the exposed and shallow layers of the earth's surface. One author describes it as being "nonlinear, plastic, absorptive, dispersive, anisotropic, and non-homogeneous." With the wide variation of material properties from one locale to another even when the materials are similarly classified, it is not surprising that crater results exhibit considerable scatter. The results of a set of carefully controlled cratering experiments conducted at WES in materials that were probably as homogeneous as nature provides exhibited deviations in the range of $\pm 10\%$, which is believed to be what might be regarded as minimal scatter. Most experiments are characterized by scatter in the range of ± 30 to 40% .

17. The extent to which the various properties of the medium affect the cratering process is somewhat uncertain. Tests have never been conducted in sufficient number or in sufficient detail to establish the relative influence of each major soil parameter on the total process. However, it would seem from an intuitive point of view that the greatest influence should be attributed to the moisture content and strength properties. Actually, these two variables are so closely related that they cannot be isolated. The strength properties referred to here are those pertaining to conditions of dynamic loading. The other properties of the medium, such as density, void ratio, etc., are believed to produce second- or third-order effects and are therefore of little consequence in developing an empirical solution of the cratering problem.

Position of Charge

18. The position of the charge, relative to the air-ground interface, is also a prime factor in determining the crater size and shape, since the charge position relative to the interface fixes the amount of energy

partitioned between the two media. Most of the energy released by charges placed above the interface goes directly into the air; consequently, charges in this position are ineffective as crater-producing explosions. Charges placed on or below the air-ground interface are much more effective since there is direct coupling of the energy to the earth medium. Hence, these charge positions are of principal interest and are considered in greater detail in this study. The results of above-surface detonations are reported simply as a matter of academic interest.

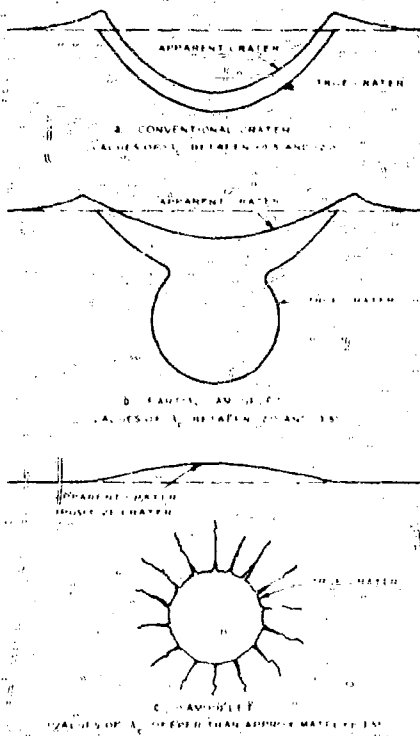


Fig. 1. Typical crater shapes and the range of charge positions with which they are associated

19. The gamut of charge positions observed has been divided into three general groups, namely, the above-ground regime, the air-ground interface, and the below-ground regime (see tabulation in paragraph 12). Charges placed in the below-ground regime may be further grouped as to crater shape (fig. 1). From experimental evidence, it has been established that in most in-situ materials, conventional craters are formed when the value of the reduced charge position λ_c lies between +0.5 and -2.0 (fig. 1a). Partial camoufllets (fig. 1b) are formed when λ_c lies between approximately -2.0 and -3.5, and in materials exhibiting appreciable cohesive strength, full camoufllets are formed when $\lambda_c \lesssim -3.5$ (fig. 1c).

PART IV: DISCUSSION OF SCALING CONSIDERATIONS

20. The purpose of the various experimental explosion-effects programs tabulated in the Compendium has been to formulate a scaling law for the various effects which will within itself be valid, or through the use of scaling factors can be used to predict the effects of much larger explosions. Most of the research has been directed toward assessing the effects of nuclear weapons by using high explosives as a small-scale energy source. Since this report does not consider craters resulting from the detonation of a nuclear source, the scaling effects that are discussed herein apply only to HE detonations of up to 1,000,000 lb of TNT. The following several paragraphs discuss the scaling aspects of the cratering problem in general and point out reasons for the failure of the scaling laws to predict results over wide ranges of explosive yields and types of media.

21. Any dimension of a crater, such as radius, depth, volume, etc., in a general sense is a function of the: weight of the charge (W , lb); shape of the charge (C_s , dimensionless); casting or packing density of the explosive (ρ_c , lb-sec²/ft⁴); energy density of the explosive (ϵ_p , ft-lb/ft³); detonation velocity of the explosive (V_d , ft/sec); density of the medium cratered (ρ_m , lb-sec²/ft⁴); moisture content of the medium in per cent by weight (μ_c , dimensionless); elastic properties of the medium (E_m , lb/ft²); strength properties of the medium, i.e. compression, shear, and tension (σ_m , lb/ft²); void ratio of the medium (v_m , dimensionless); Poisson's ratio of the medium (μ , dimensionless); and position of the charge relative to the air-ground interface (Z , ft).

Expressed mathematically

$$r, d, V, \text{ etc.} = f(W, C_s, \rho_c, \epsilon_p, V_d, \rho_m, \mu_c, E_m, \sigma_m, v_m, \mu, Z) \quad (1)$$

Although this expression may represent almost the absolute solution of the cratering problem, it is recognized that to acquire sufficient experimental data wherein each of the independent variables are fully described borders

on the ridiculous. In the first place, there are no methods at the present time for evaluating the various properties of the soil in situ when the soil is exposed to transient loads; hence, the problem, for practical and economic reasons, must be grossly simplified.

22. For the purpose of analyzing the data presented in the Compendium⁷ the following seems reasonable:

$$r, d, V, \text{ etc.} = f(W, Z, S) \quad (2)$$

where r is the crater radius, d the crater depth, V the crater volume, W the charge weight (lb of TNT), Z the charge position relative to the air-medium interface, and S a soil resistance function described by soil type only. Such an approach represents what might be considered a first-order solution of the cratering problem and, in view of the data available for analysis, is the only practicable type of solution.

23. If the problem were as simple as outlined above, a curve relating the dimensions of the crater, the charge weight, and the charge position relative to the interface could be developed for each soil type by using dimensionless groupings of these variables as developed from dimensional analysis. For example, if the cube root of the charge weight is considered a linear dimension (this is an entirely proper assumption since $W = \gamma \frac{4}{3} \pi r_c^3$, from which $r_c = f W^{1/3}$), a plot of $d/W^{1/3}$ or $r/W^{1/3}$ versus $Z/W^{1/3}$ for various soil types provides a graphic solution of the problem. However, the problem is not that simple, and there exist deviations from the scaling procedure implied by the classic cube-root law (Hopkinson's law). The most important deviation from the implied principles of similarity occurs not in the very early history of the explosion, but after emission of the shock wave and after the termination of essentially hydrodynamic behavior. The later stages of crater formation are highly dependent on gravitational forces; for example, the effect of gravity causes the shear resistance of the soil to increase with an increase in the scale of the explosion. Since gravity is not readily scalable, this phenomenon will deviate from the laws of similarity associated with cube-root scaling. Deviations in scaling are to be expected when it is realized that parameters such as the density of the medium, its particle size, and

its strength properties cannot be scaled in proportion to the ratio of the cube roots of the scaled charge and prototype charge.

24. Experimental results show that cube-root scaling is approximately valid when charge weights range from about 1 to 1000 lb. As the range of charge weights is enlarged to include charges up to several tens of thousands of pounds, the deviation in cube-root scaling becomes more discernible. Even at this scale, the deviations are not objectionably large because the physical size of the charge is scalable and its size tends to hold the deviations to a minimum. As the energy density of the explosive is increased to greater and greater amounts, the deviations continue to increase such that for nuclear weapons, scaling from TNT sources on the basis of the cube-root law yields completely misleading results.

25. In summary, the cube-root law is invalid over a wide range of yields; particularly is this true when the explosives involved have widely varying energy densities and detonation velocities. A first-order approximation of the cratering problem may be obtained through the use of cube-root scaling when TNT, or a nearly equivalent type of explosive, is the only energy source used. In this report, the data contained in the Compendium are analyzed to reflect any scale effect due to a wide variation in charge weight by plotting crater dimensions as a function of charge weight. Hence, a best-fit scaling procedure (based on the least-squares method) is used to minimize scatter and to increase the accuracy of prediction methods.

PART V: ANALYSIS OF CRATERING DATA

Available Data

26. Crater measurements suitable for use in analysis are available from approximately 1000 shots involving the use of TNT or some other explosive for which conversion factors are available to make possible the reduction of its yield to an equivalent TNT yield.⁷ The charges were detonated in more than 20 different media and 24 types of explosives were employed, as summarized in table 1. In order to establish prediction curves for frozen ground and ice, it was necessary to use the weight of charge recorded, since conversion factors were not available for the types of explosives used in these test programs. The propriety of doing this may be questionable, but in the absence of proper conversion factors, no other procedure seemed realistic.

27. The ranges of variables (charge weight, depth of burial of charge, and reduced depth of burial of charge) are presented in table 2. From this table, it would appear that sufficient data are available from which a rigorous empirical solution of the cratering problem might be made. However, the fact is that the data are not well distributed over the range of variables stipulated. In some cases, there is an overabundance of data for certain values whereas for other cases there is a definite scarcity of useful data. These areas of "famine or feast" result from a lack of coordination in past research efforts and the fact that a considerable portion of the data as a whole was derived from research projects wherein crater measurements were by-products only and were inadequately reported.

28. Certainly, any future explosion-effects research resulting in crater formation should report such measurements in order to supplement data listed in the Compendium.⁷ Any further research that may be directed toward advancing the state of the art of predicting the size of explosively generated craters should be carefully planned to ensure as broad a coverage of the ranges of primary interest as possible. To date, no work of any real significance has been done to ascertain the effects of energy density and detonation velocity on the cratering efficiency of various types of explosives. This should be done to assist in developing a more workable

theory of the cratering problem in general. It is further believed that work in this area may well lead to a more realistic means of scaling HE results into the nuclear range with confidence.

Methods of Analysis

29. To determine the scaling trends that would best fit the data tabulated in the Compendium,⁷ plots of crater depth and radius as a function of charge weight for the various types of soil and for the selected ranges of charge position were made (see plates 1-51).^{*} Plates 1-6 and 30 and 31 present, for various types of soil, crater dimensions plotted as a function of charge weight for broad ranges of charge position. These ranges were made large in an attempt to group together as many individual crater measurements as possible without assuming similar behavior to exist over an absurdly broad range. This procedure permits the plotting of hundreds of points over a wide range of charge weights. Of course, it also presupposes that there exists a balance in the number of charges positioned over the range of charge positions and weights involved. Otherwise, if more low-yield shot results from deeply buried charges were available compared to high-yield shot results, most of which were obtained from shallowly placed charges, the line of best fit would have a biased and flatter slope than a balanced set of results would exhibit. Plots of crater dimensions versus charge weight for more specific charge positions (having a relatively narrow range) and for various types of soil are presented in plates 7-12 and 32-37. The remaining plates (plates 13-29 and 38-51) show the crater radius or depth as a function of the charge weight for a specific soil type and for a specific charge position.

30. Limit lines are shown in plates 1-51 (except 40 and 41) which describe an interval within which 95% of the experimental data fall. The limit lines also provide an indication of the levels of scatter associated with the phenomenon. Particularly is this true where an appreciable number of observations are involved. The limits also illustrate that there is

* The reference numbers that appear in all plates of this report refer to similarly numbered items in the Bibliography contained in the Compendium.⁷

less scatter associated with the measurement of crater radius than with crater depth.

31. The line of best fit and its equation, as determined by the method of least squares, is shown also in plates 1-51. The form of each of these equations is:

$$r \text{ or } d = K (W)^n \quad (3)$$

wherein the value of n establishes the scaling trend of the plotted data. In arriving at general scaling trends for all of the plots (plates 1-51), it was necessary to consider each value of n in which the number of observations, the distribution of the plotted points, and the scatter were all factors. Since the true crater data are the more reproducible, these data were more prominently considered than portions of the apparent crater data. Above-ground shots were not considered in establishing the scaling trends.

32. The values of the exponent n were tabulated and cross-tabulated with various parameters. The end result of the analysis of the tabulations and data plots presented in plates 1-51 was the decision that crater depth is more nearly described by $W^{0.3}$ scaling and crater radius by $W^{1/3}$ scaling. Since the crater depth scales differently than the radius, the shape of the crater will depend on the yield of the explosion (scale of the experiment).

Results of Analysis

Prediction curves

33. To establish crater prediction curves based on the scaling laws decided upon, it was necessary to reduce all the radius and depth measurements by $W^{1/3}$ and $W^{0.3}$, respectively. No effort was made to analyze crater volume or the crater lip height, primarily because of the lack of sufficient data. (Normally, the crater volume may be satisfactorily determined by computations made from the crater profile shaped to conform to the known radius and depth.) The reduced crater depth and radii ($d/W^{0.3}$ and $r/W^{1/3}$, respectively) were then plotted as a function of the reduced

charge position ($Z/W^{1/3}$) for those types of media for which sufficient data were available. The crater prediction curves are presented in plates 52-71. In each plate, nomographs are provided to assist in making estimates of crater dimensions for a variety of charge weights and depths of burial. Apparent crater prediction curves are shown in plates 52-63 for wet clay, moist clay, dry clay, wet sand, dry-to-moist sand, loess, silt, frozen ground, basalt, shale, ice, and snow, respectively. True crater curves are shown in plates 64-71 for moist clay, dry clay, basalt, chalk, granite, marlstone, sandstone, and shale, respectively.

Variation of data

34. A study of the scatter exhibited by the experimental data shows that in soils crater radius measurements vary approximately 20% and crater depth measurements approximately 30% regardless of the position of the charge. Although a marked tendency exists which implies less scatter in the measurement of true craters, the paucity of the data precludes a specific conclusion to this effect. A similar study of scatter associated with measurements in rock indicates a scatter of approximately 40 to 50% for crater depth, and about 30 to 40% for crater radius.

The maximum crater

35. The crater prediction curves (plates 52-71) provide a graphic picture of the influence of the charge position on crater size. From the plots, it can be seen that the maximum apparent crater results from a charge positioned such that

$$-1.0 > \lambda_c > -1.5$$

Similarly, the true crater is maximum when the reduced charge position is approximately equal to -2.0.

Comparison of apparent and true craters

36. Where direct comparisons of apparent and true crater dimensions are possible (compare plate 53 with 64, 54 with 65, 60 with 66, and 61 with 71), the following relations appear applicable. First, the true crater radius is roughly 10 to 20% larger than the apparent crater radius. Second, this difference in crater radii seems true regardless of the charge

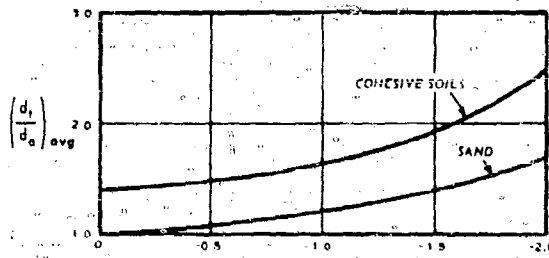


Fig. 2. Ratio of true crater depth to apparent crater depth for various charge positions

position and type of medium. On the other hand, the ratio of the true crater depth to the apparent crater depth is highly sensitive to charge position as can be seen in fig. 2. Thus, estimates of the true crater radius and depth may be made from the apparent crater radius and depth by using these factors.

Generalizations of the cratering capability curves

37. If the cratering data shown in plates 52-71 are considered together and summarized, the resulting single plot of each crater dimension can be used to present an approximate and somewhat generalized solution of the crater prediction problem. Figs. 3 and 4 present plots of this type for the apparent crater radius and depth. A study of all the crater lip information contained in the Compendium⁷ shows that the ratio of h/d varies as λ_c ; this variation is shown in fig. 5 (page 19). The same study shows also that the width of the crater lip normally varies from about 0.7 to 1.0 crater radius for charges positioned between $0 > \lambda_c > -1.0$, and is about one-half the crater radius for charges between $-1.0 > \lambda_c > -2.0$. With these three plots (figs. 3-5) and the "rule of thumb" assessment of crater lip width, the profile of any crater can be developed as long as the charge is HE and its weight does not significantly exceed 1,000,000 lb. Other restrictions, which cannot be assessed at present, should be imposed for situations wherein the medium cratered is stratified, or is highly saturated or heterogenous in nature.

Formation of camouflets

38. Generally, camouflets are formed when explosive charges are detonated at depths of burial equal to or greater than approximately $3.5 W^{1/3}$ ($\lambda_c \approx -3.5$). The stability of the camouflets depends to a pronounced degree on the strength properties of the material, particularly the cohesive properties, for they, to a large degree, determine the arching characteristics of the soil. Thus, the maximum size cavity that can be formed in a given material by the use of explosives cannot be determined by

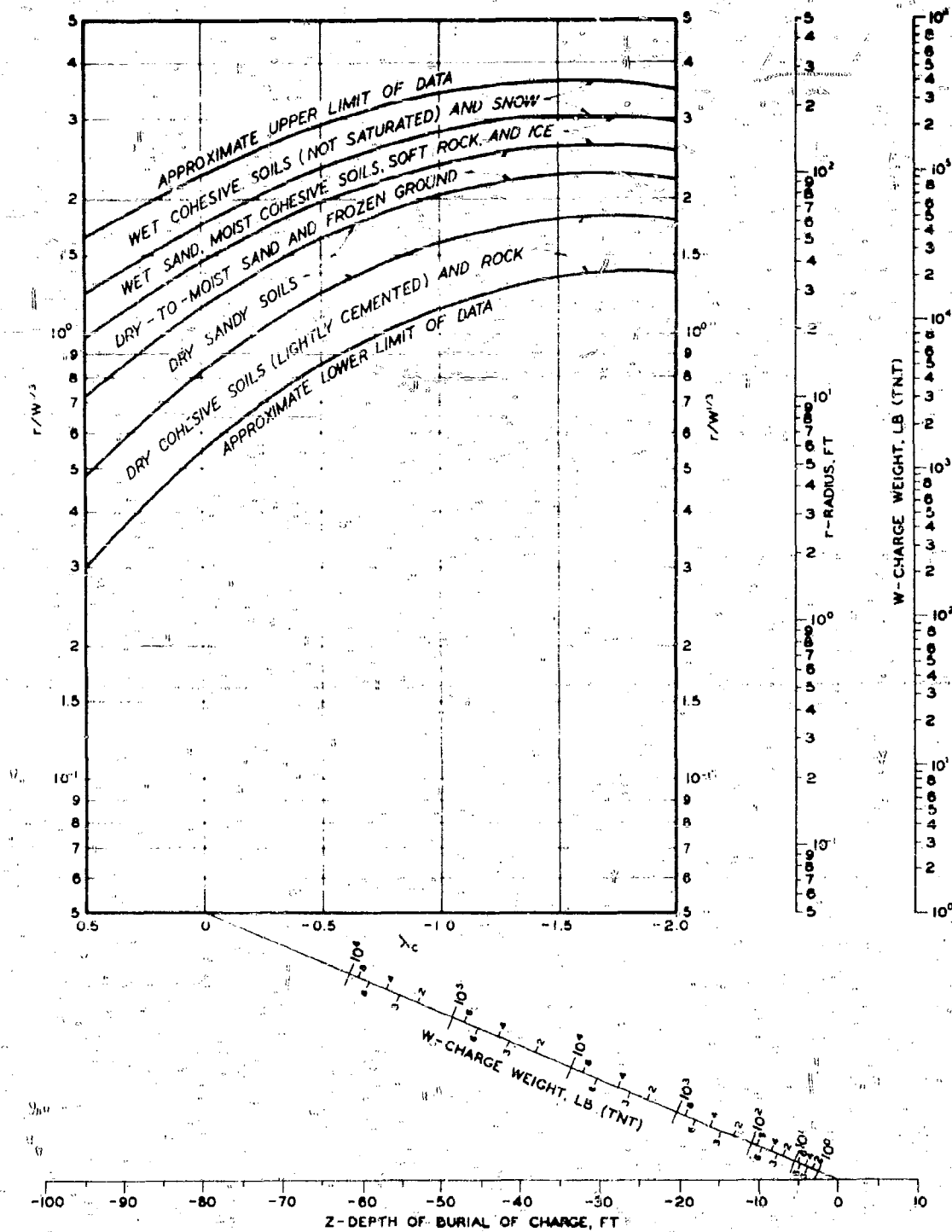


Fig. 3. Nomograph for determining the apparent crater radius in various media

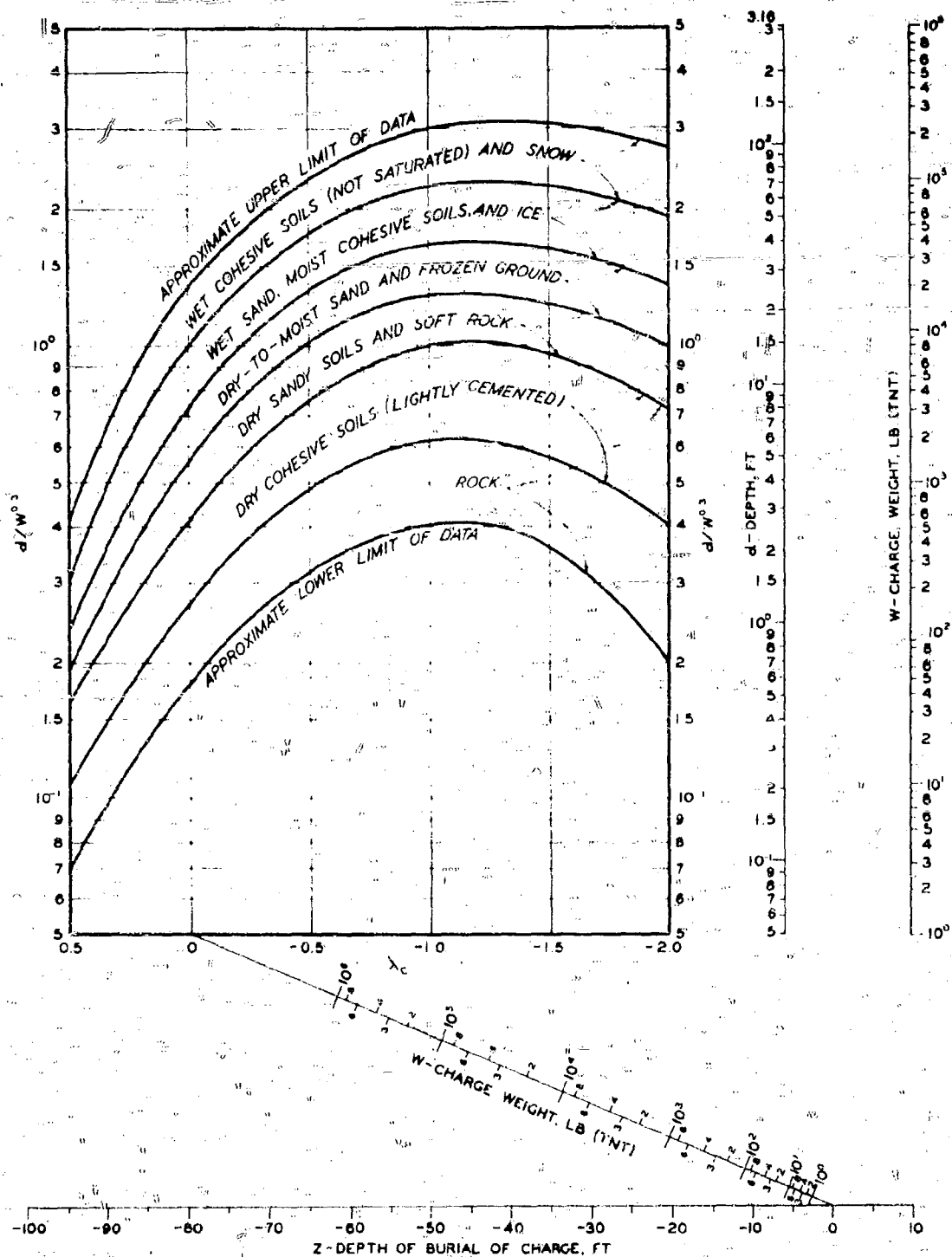


Fig. 4. Nomograph for determining the apparent crater depth in various media.

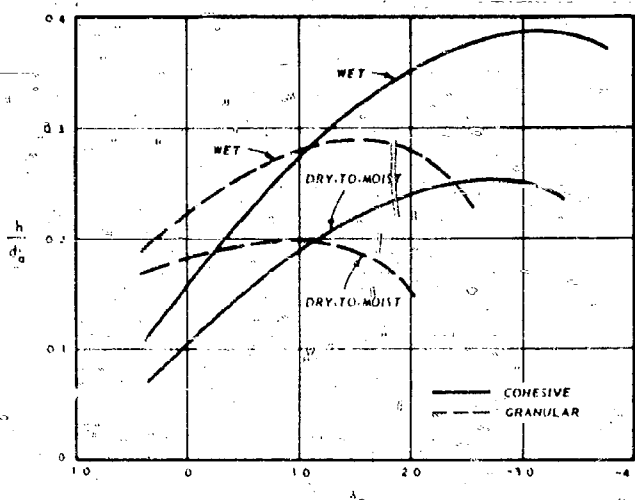


Fig. 5. Ratio of crater lip height to apparent crater depth for various charge positions

extrapolation of experimental data without detailed considerations of the material's properties. Experimental evidence currently available⁶ indicates that for cohesive soils such as loess and clay (each having moderate water contents) the camouflet diameter will be closely approximated by:

$$D_v \text{ or } D_h = (2.3 \pm 0.4)W^{1/3} \quad (4)$$

where D_v and D_h are the diameters of the camouflet in the vertical and horizontal directions, respectively. The same experiments⁶ showed that for all practical purposes the two diameters were equal. The possibility that camouflets can be formed in granular materials is questionable; however, since granular materials do develop some shear strength (friction) with depth, it is conceivable that such cavities could be formed if charges were buried sufficiently deep.

39. For the purpose of predicting the size camouflet that will be formed by an explosive charge properly positioned in a cohesive soil mass, it is recommended that equation 4 be used to estimate the camouflet's diameter. The soil properties should then be carefully considered to determine the ability of the soil to arch over such a cavity without appreciable failure of the highly compressed shell.

PART VI: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

40. From the analysis reported herein, based upon available HE cratering data,⁷ the following conclusions were formed:

- a. The crater radius is best described by cube-root scaling, whereas the crater depth is best described when scaled as $W^{0.3}$.
- b. Cratering in soils is characterized by a $\pm 20\%$ scatter for crater radius and a $\pm 30\%$ scatter for crater depth. These scatter limits increase to ± 30 to 40% for width and ± 40 to 50% for depth when the material being cratered is rock.
- c. The maximum apparent crater is formed when $-1.0 > \lambda_c > -1.5$; the maximum true crater is formed when the reduced charge position equals approximately -2.0 .
- d. Camoufllets are formed in cohesive soils when the charge is positioned so that $\lambda_c < -3.5$.

Recommendations

41. The enormous task of compiling all HE cratering data under a single cover, coupled with the frustrations encountered in trying to develop a more refined analysis of the data than is presented herein, has led to the following recommendations:

- a. Future cratering experiments should be carefully controlled. In particular more elaborate information on the medium cratered should be obtained. Several cratering programs at the WES have shown that the scatter mentioned in paragraph 40b can be greatly reduced (to $\pm 10\%$ for crater radius and depth) by carefully controlling the moisture content and density of the artificially emplaced and compacted soils.
- b. It is also desirable that experiments be carefully planned so as to obtain a broad coverage of the range of charge positions that are of primary interest to the total problem of cratering. Where feasible, colored-sand columns should be used to delineate the true crater.⁵
- c. A study of energy density-detonation velocity effects on cratering is needed. It is known that cratering efficiency decreases as the energy density of the explosive increases, but how the efficiency changes with energy density on a

quantitative basis is not known. Such a study would very probably indicate better ways to relate nuclear and high explosives from the standpoint of cratering effectiveness.

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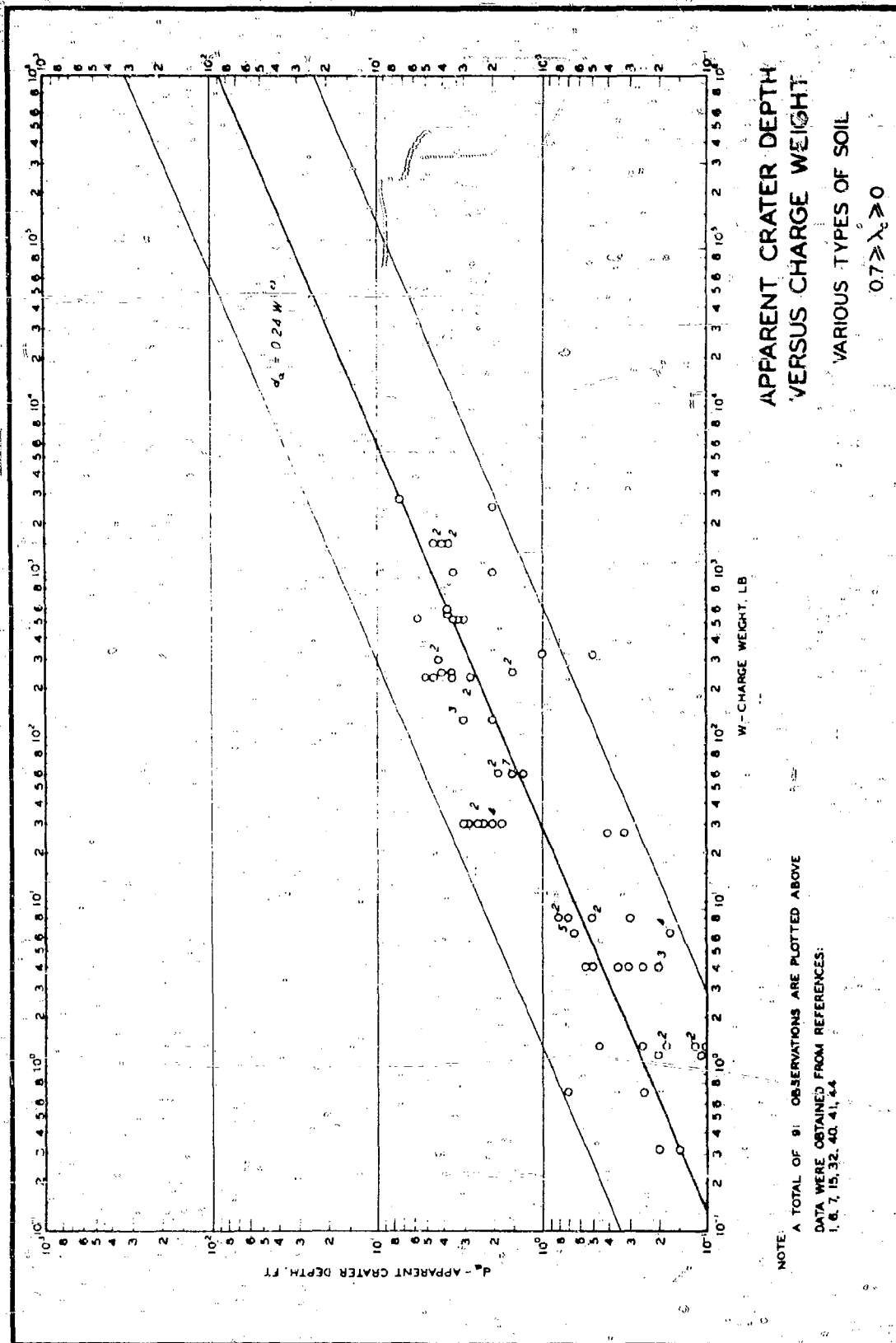
1. British Ministry of Home Security, Road Research Laboratory, A Comparison of the Crater Dimensions and Permanent Earth Movements in Clay, Sand, Chalk, and Gravel Soils Due to the Explosion of Buried Bombs (U). AFSWP-337 (SECRET report), March 1941.
2. Livingston, C. W., Excavations in Frozen Ground (U). U. S. Army Snow Ice and Permafrost Research Establishment, SIPRE Report 30 (UNCLASSIFIED report), July 1956.
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5. U. S. Army Engineer Waterways Experiment Station, CE, Effects of Stemming on Underground Explosions (U). Technical Report No. 2-438 (UNCLASSIFIED report), Vicksburg, Miss., January 1957.
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Table 2

Ranges of Variables in HE Cratering

Media	Number of Shots	Ranges of Variables			Reduced Depth of Charge λ_c
		Weight of Charge W, lb	Depth of Charge Z, ft		
Soil					
Unshaped charges:					
Wet clay	101	8.0 to 2,560	+0.83 to -16.8	+0.13 to -4.20	
Moist clay	89	0.5 to 200	0.0 to -12.0	0.0 to -12.0	
Dry clay	29	8.0 to 320,000	+3.50 to -35.0	+0.51 to -3.07	
Indefinite clay	7	1.0 to 1.0	+0.37 to -0.38	+0.35 to -0.36	
Wet sand	62	1.18 to 40,000	+3.50 to -21.0	+0.51 to -3.07	
Dry-to-moist sand	89	0.32 to 40,000	+1.29 to -6.79	+0.69 to -2.84	
Loess	70	0.5 to 64	0.0 to -14.0	0.0 to -14.0	
Silt	84	8.0 to 1,045	+1.85 to -1.50	+0.62 to -0.50	
Shaped charges:					
Clay	45	0.25 to 2,790	+3.90 to -22.0	+0.36 to -4.29	
Dry clay	15	1.0 to 3	0.0 to -3.50	0.0 to -3.50	
Clay loam	9	1.0 to 1.0	0.0 to -3.50	0.0 to -3.50	
Sandy clayey silt	22	8.0 to 1,080	-4.20 to -21.0	-2.10 to -2.10	
Silty sandy clay	14	8.0 to 64	-4.20 to -8.40	-2.10 to -2.10	
Various soils	36	8.0 to 3,200	-4.20 to -31.0	-2.10 to -2.10	
Frozen ground	577	0.014 to 20.16	-0.42 to -5.94	-0.39* to -4.0*	
Rock					
Basalt	18	8.0 to 200	0.0 to -12.0	0.0 to -3.60	
Chalk	17	0.4 to 8.0	-0.8 to -19.7	-0.40* to -7.12*	
Granite	119	0.15 to 2,560	+2.50 to -17.0	-0.36 to -4.45	
Limestone	2	320 to 320	-2.50 to -6.60	-0.36 to -0.96	
Marlstone	8	1.5 to 13.5	-1.2 to -6.0	-0.80* to -4.09*	
Sandstone	131	0.5 to 320,000	0.0 to -25.0	0.0 to -3.70	
Shale	18	8.0 to 200	0.0 to -12.0	0.0 to -3.50	
Ice	112	2.5 to 40	0.0 to -18.67	0.0 to -5.57*	
Snow	70	0.50 to 6	0.0 to -8.50	0.0 to -8.94	

* Numbers are not based on TNT equivalent charge weights.



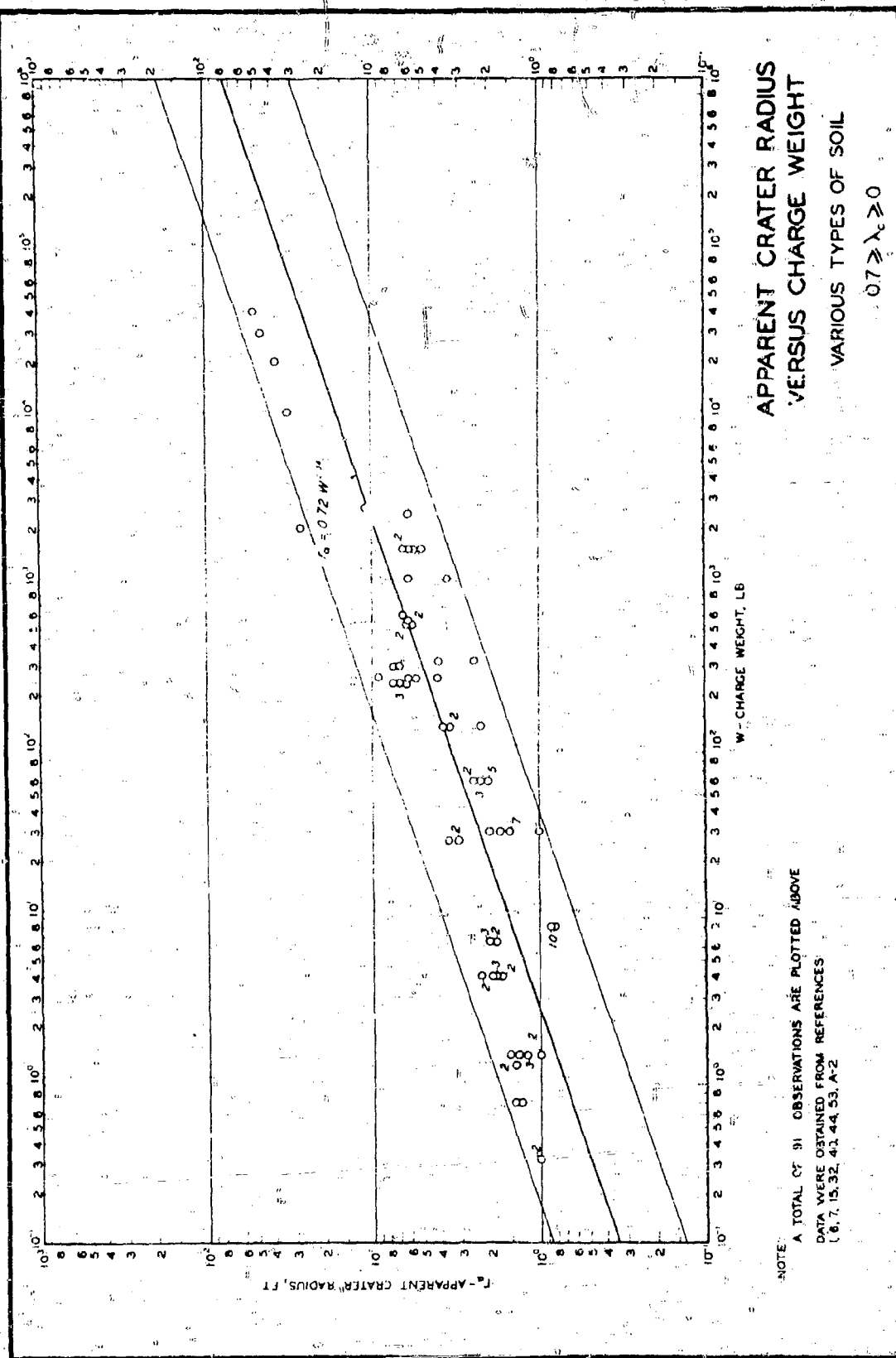


PLATE 2

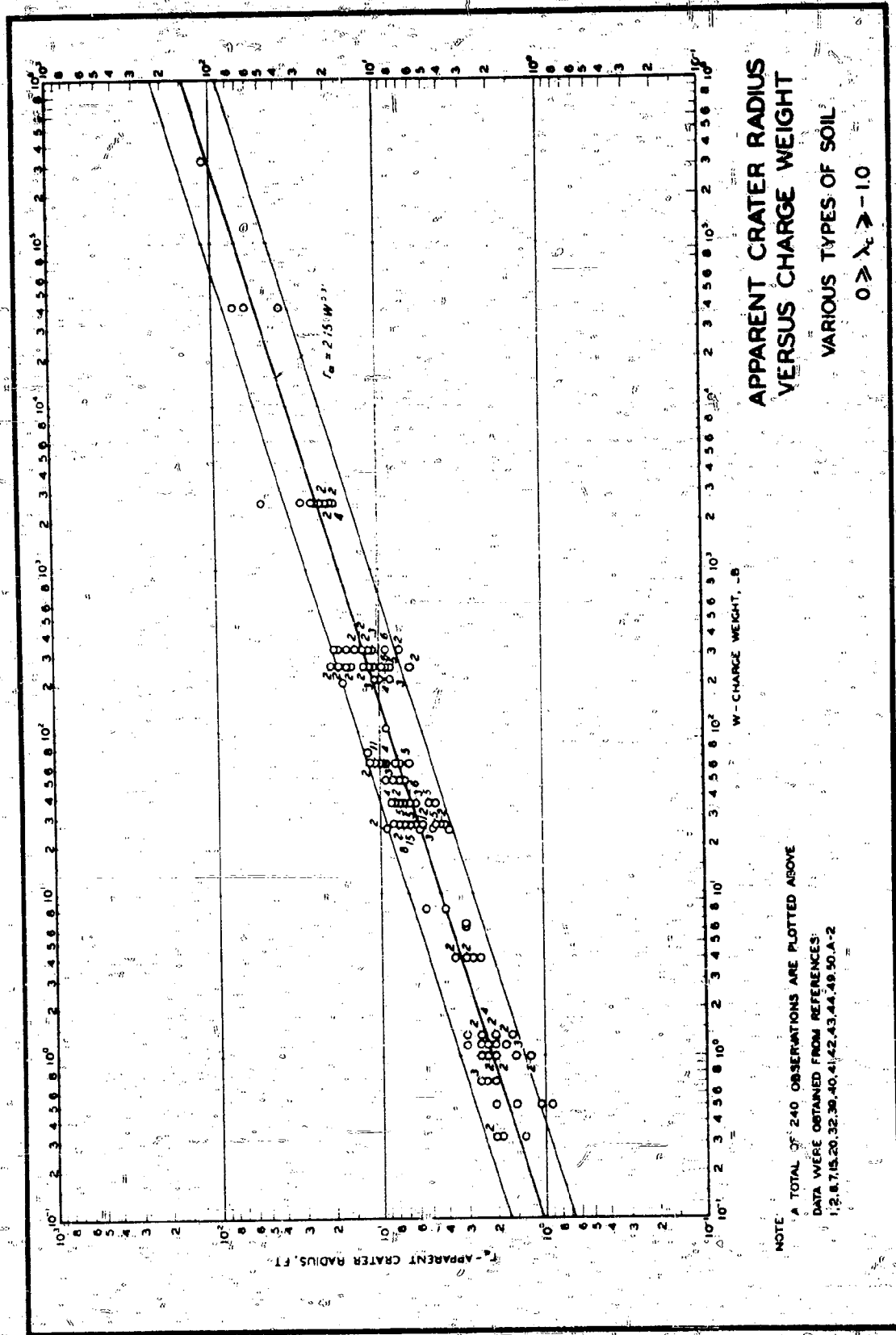


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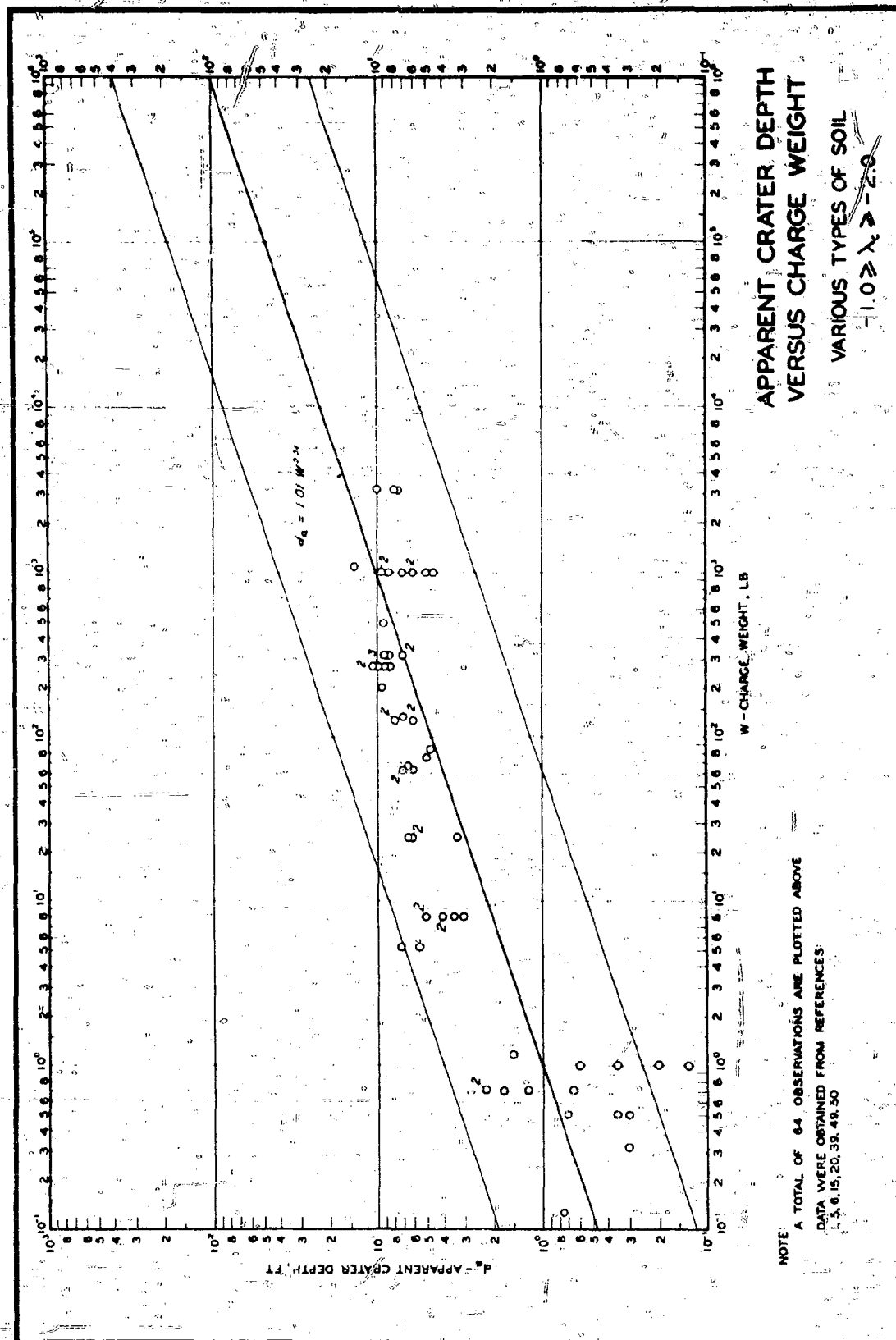
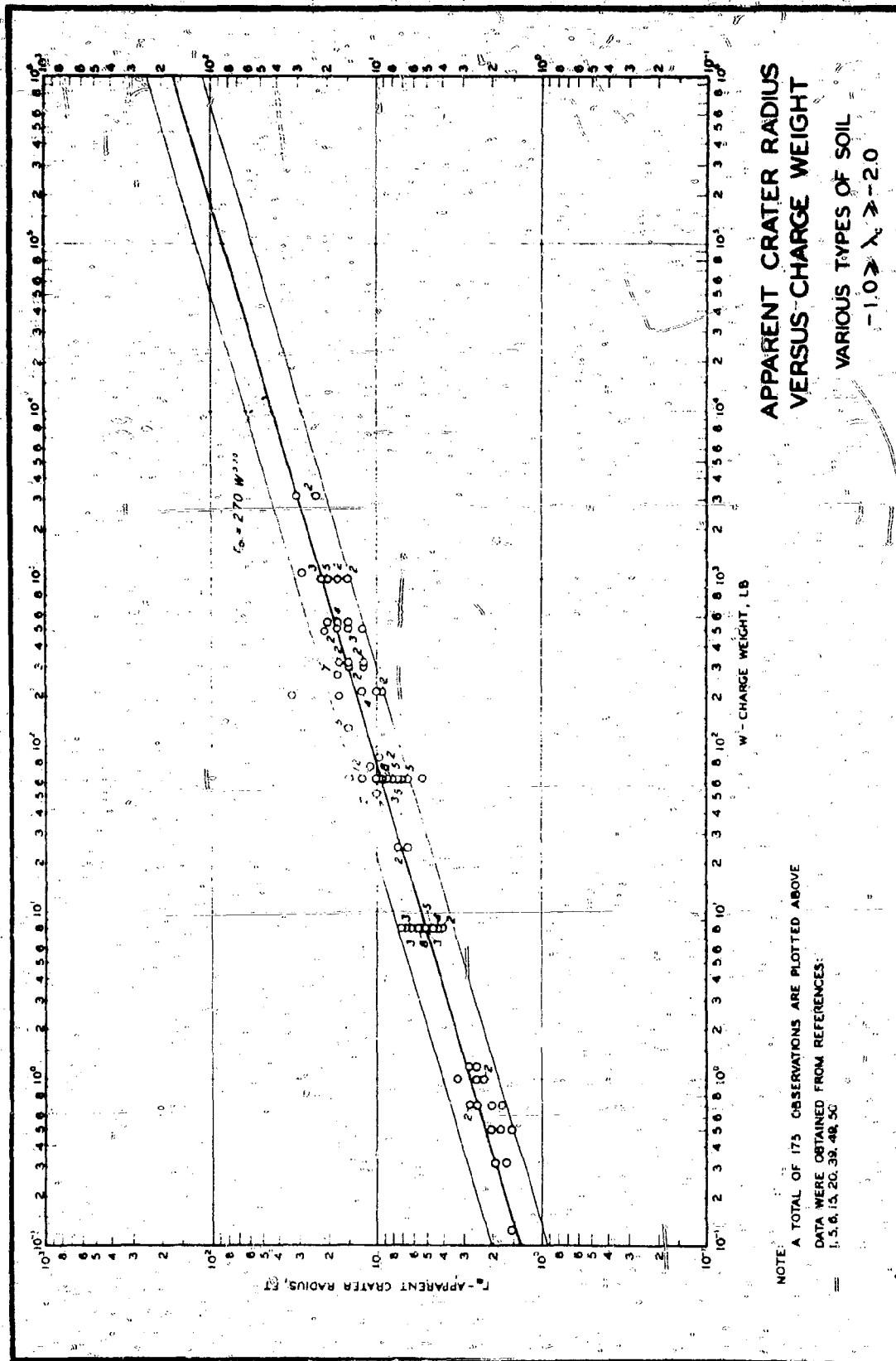
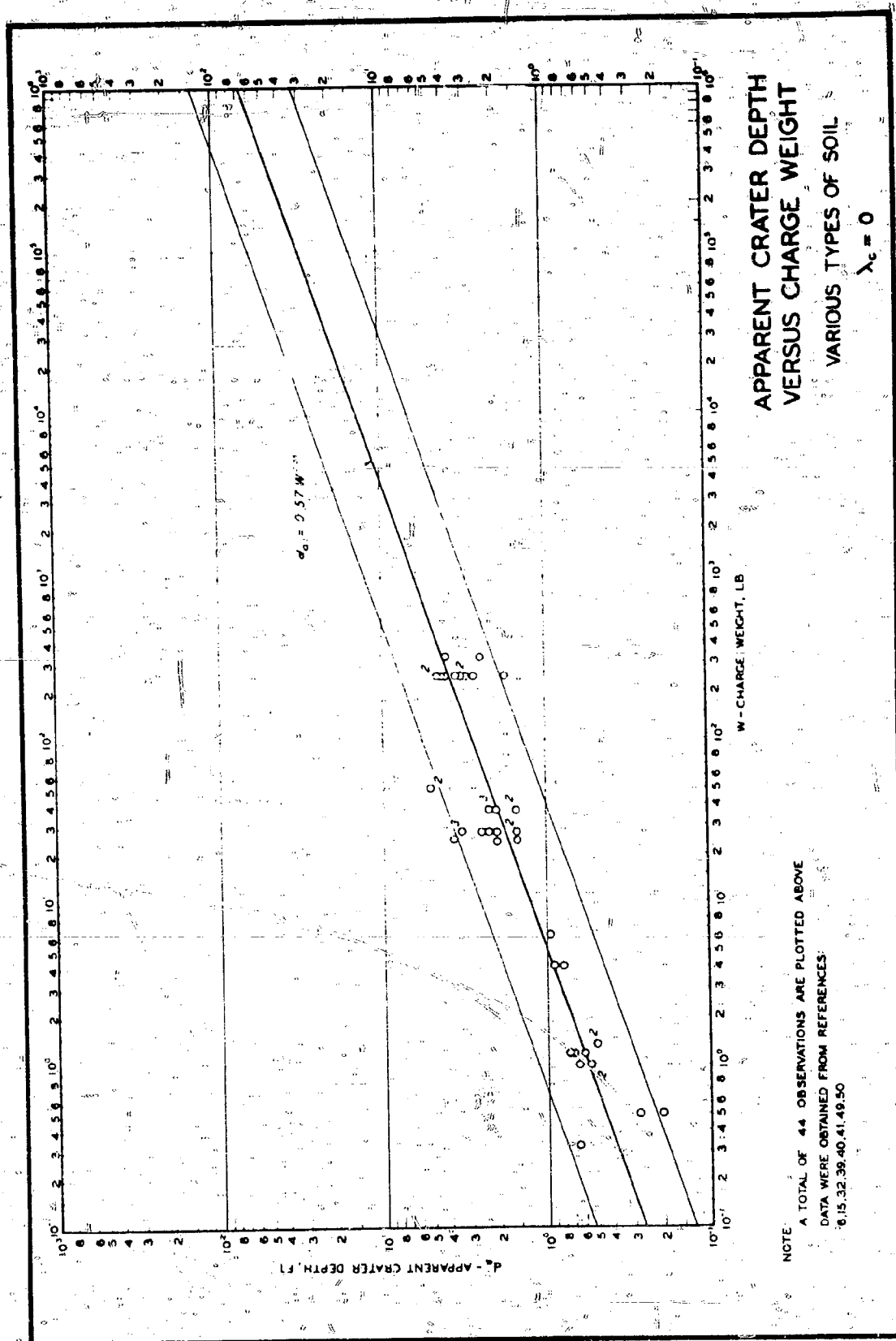


PLATE 6





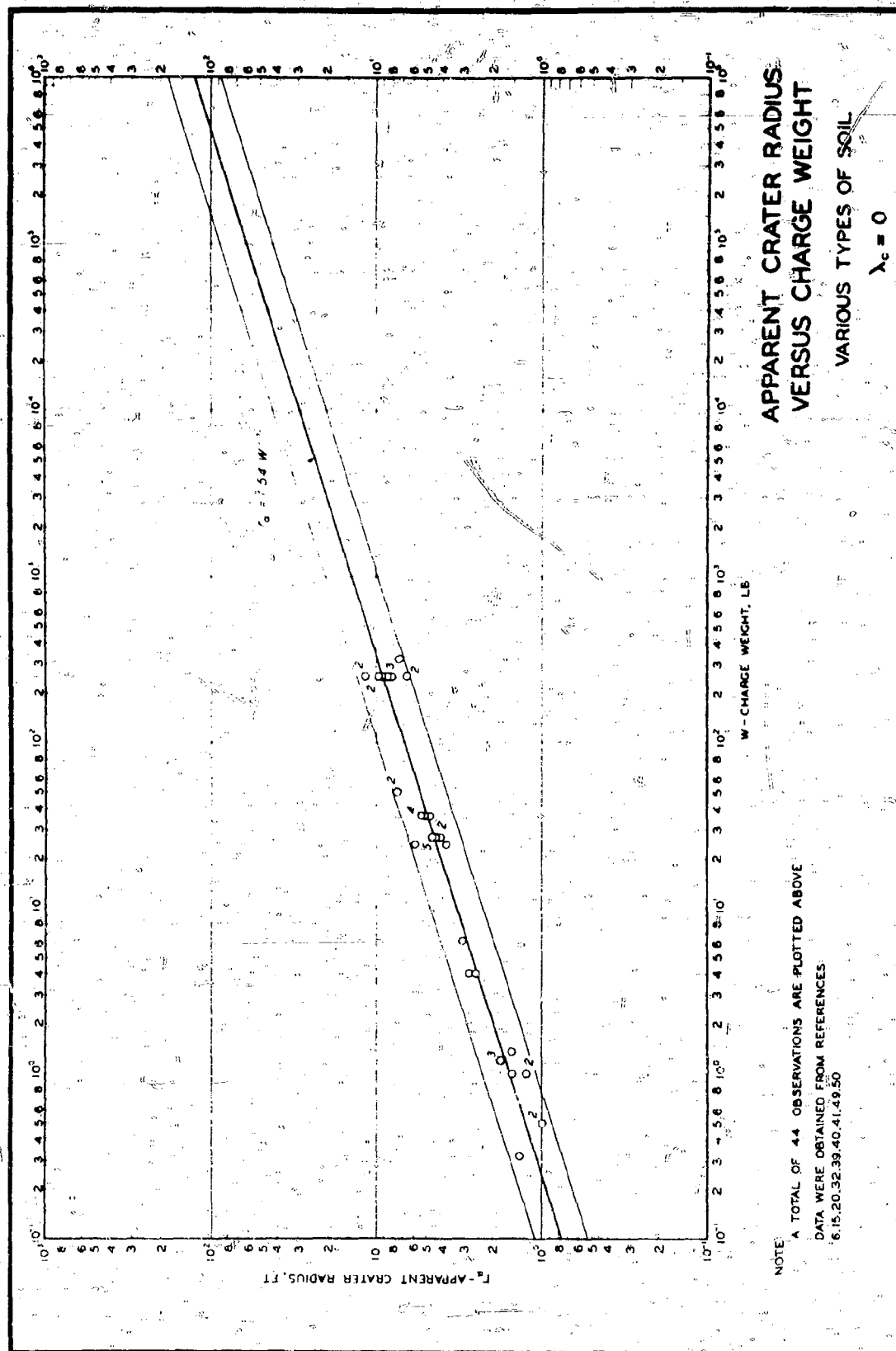
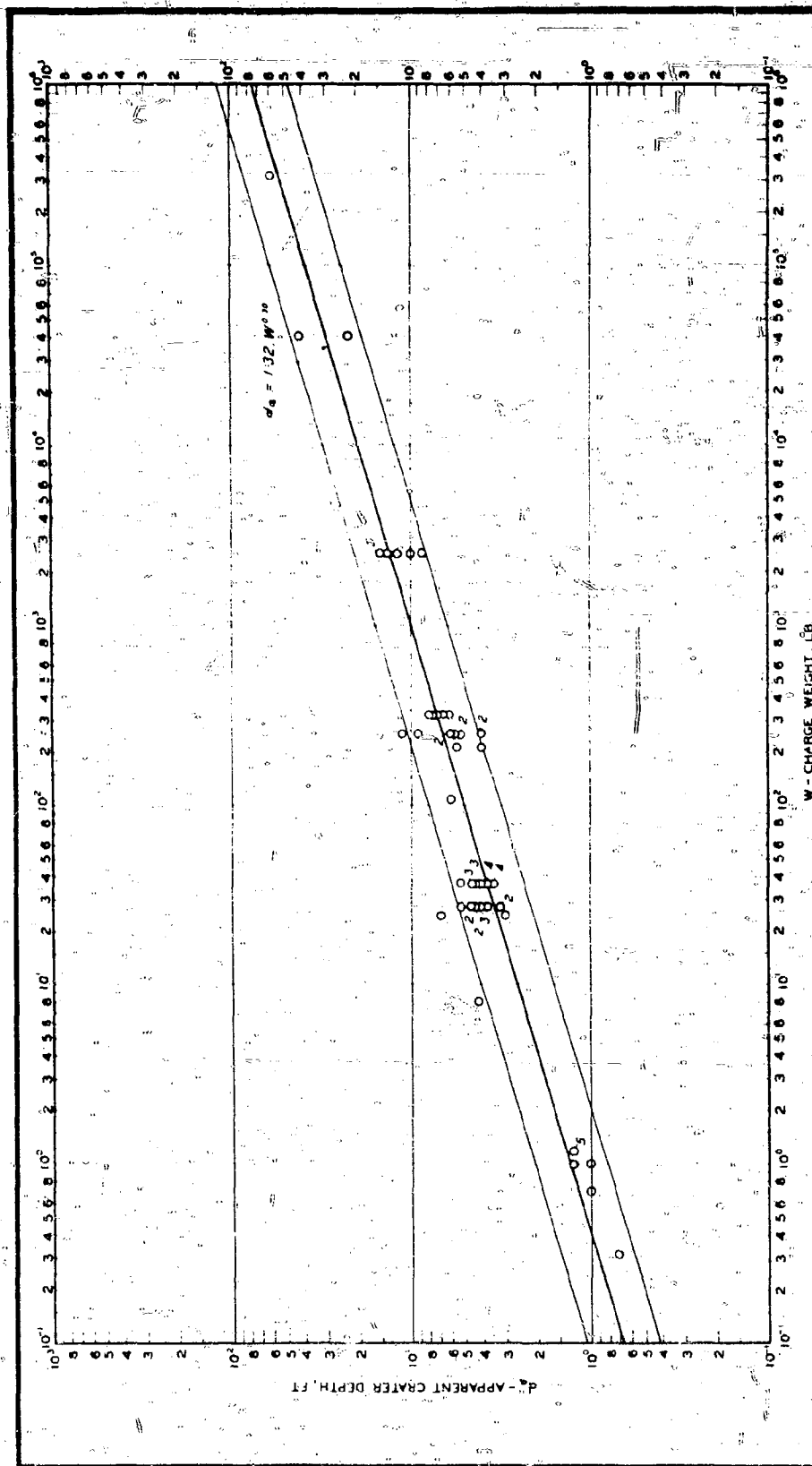
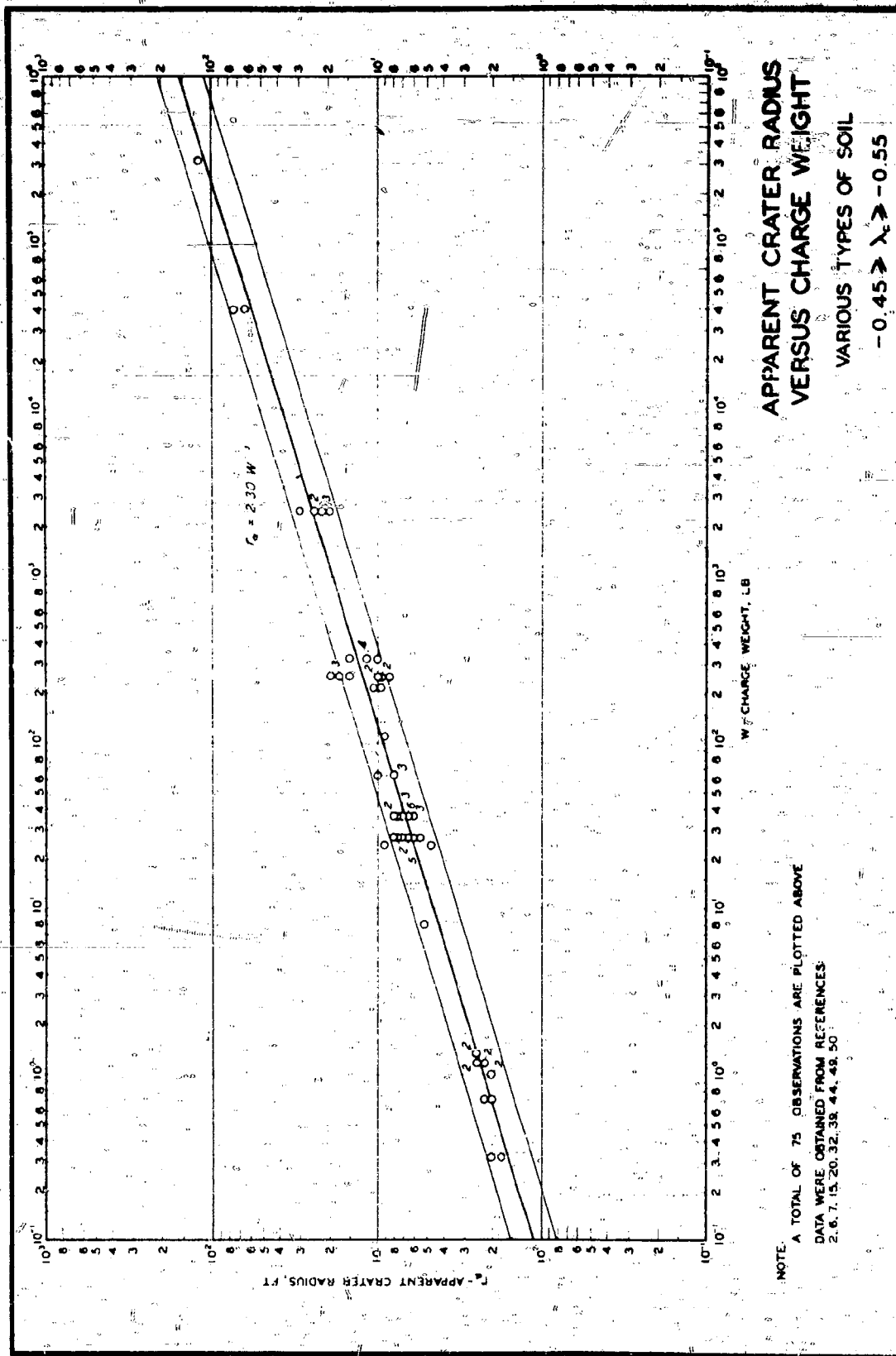


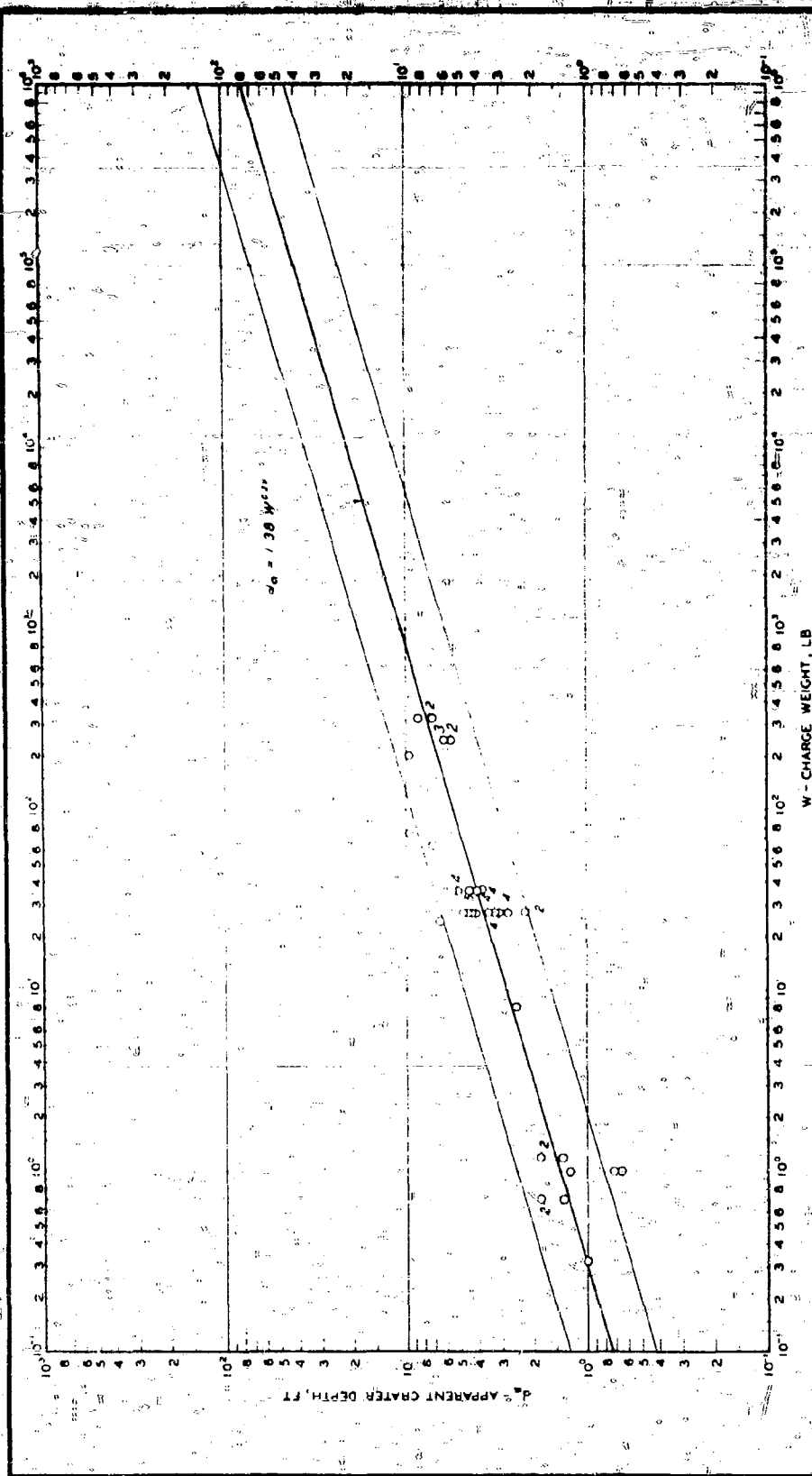
PLATE 8



APPARENT CRATER DEPTH
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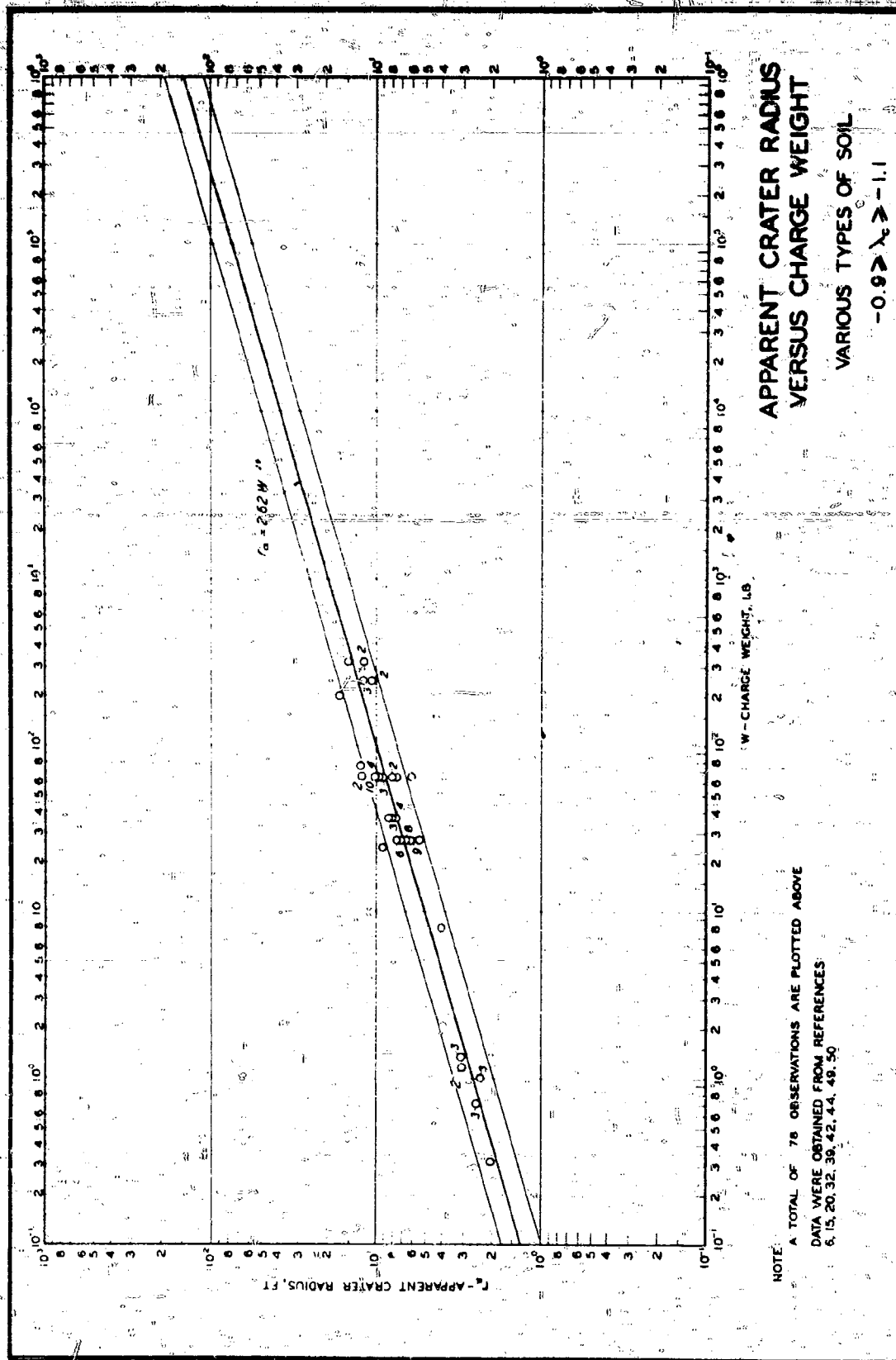
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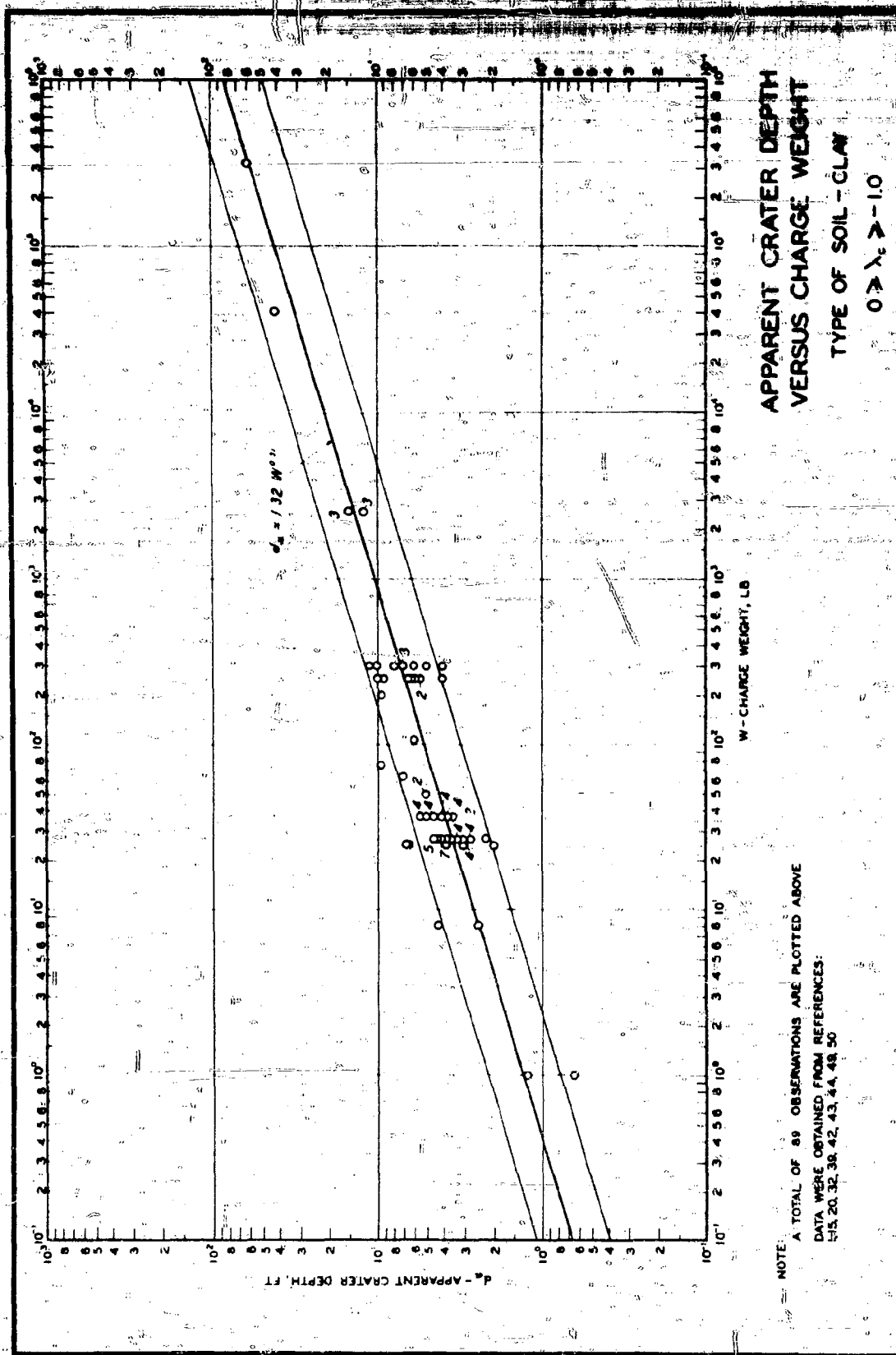


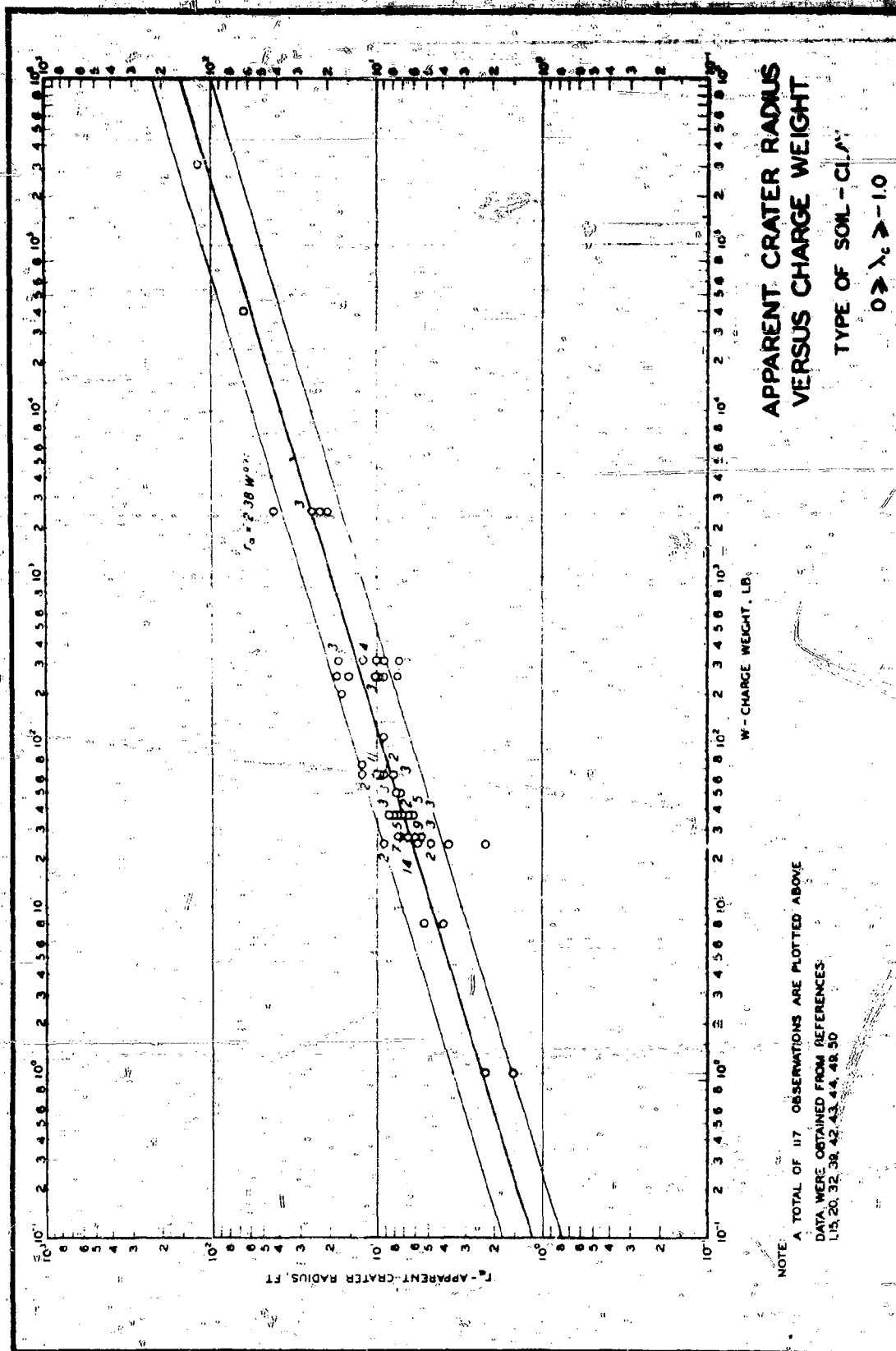


APPARENT CRATER DEPTH
VERSUS CHARGE WEIGHT
VARIOUS TYPES OF SOIL
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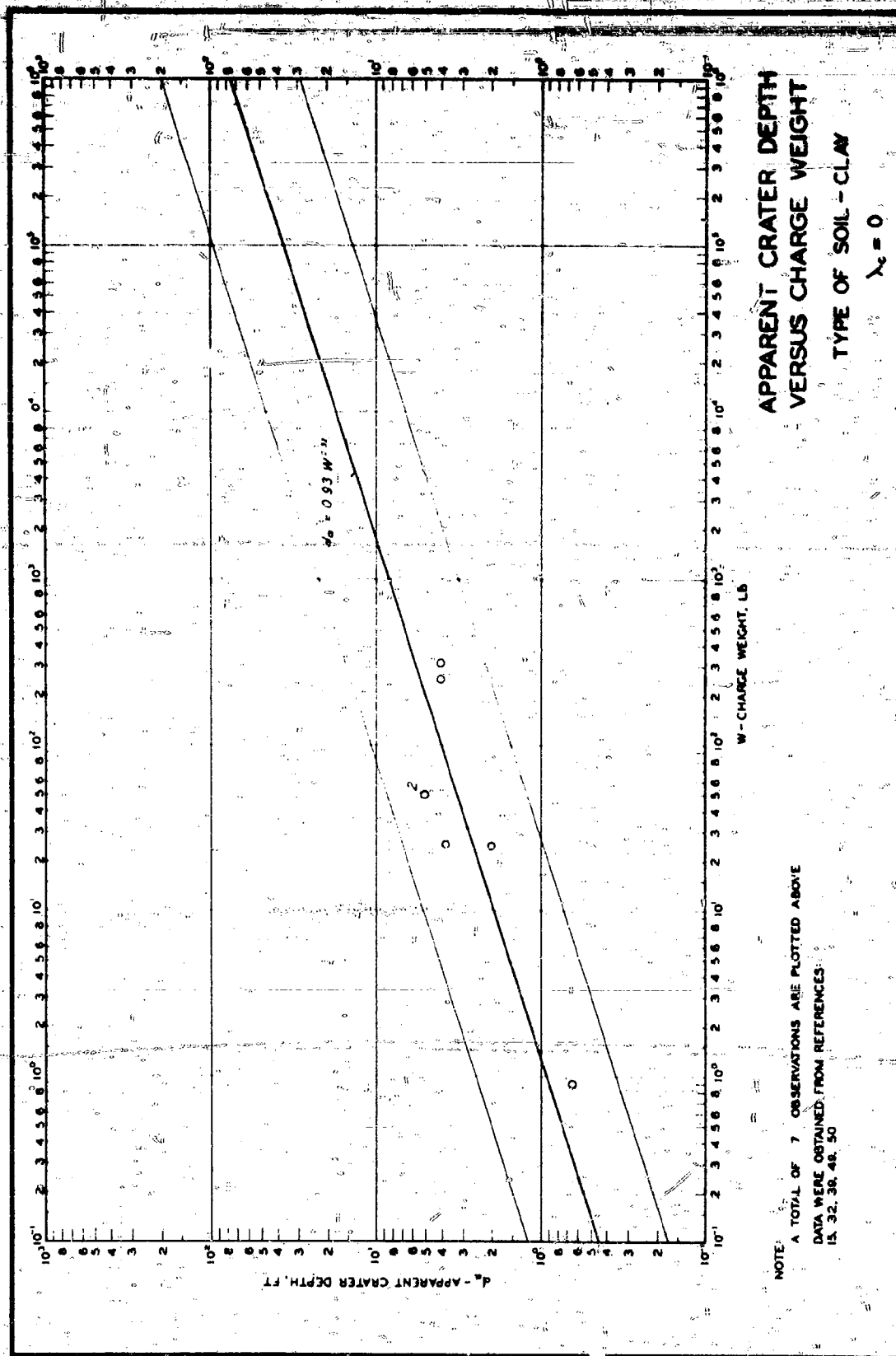
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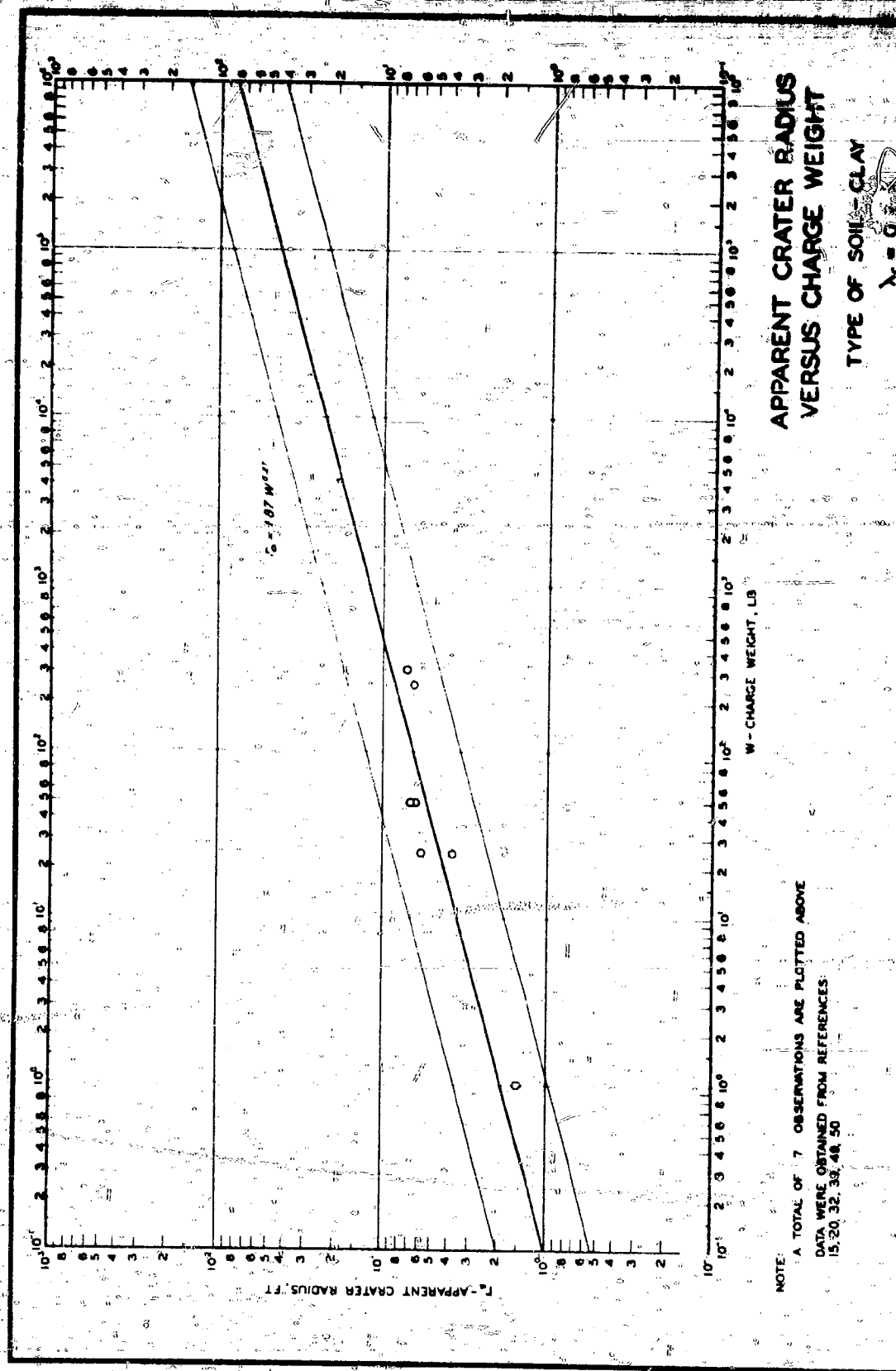
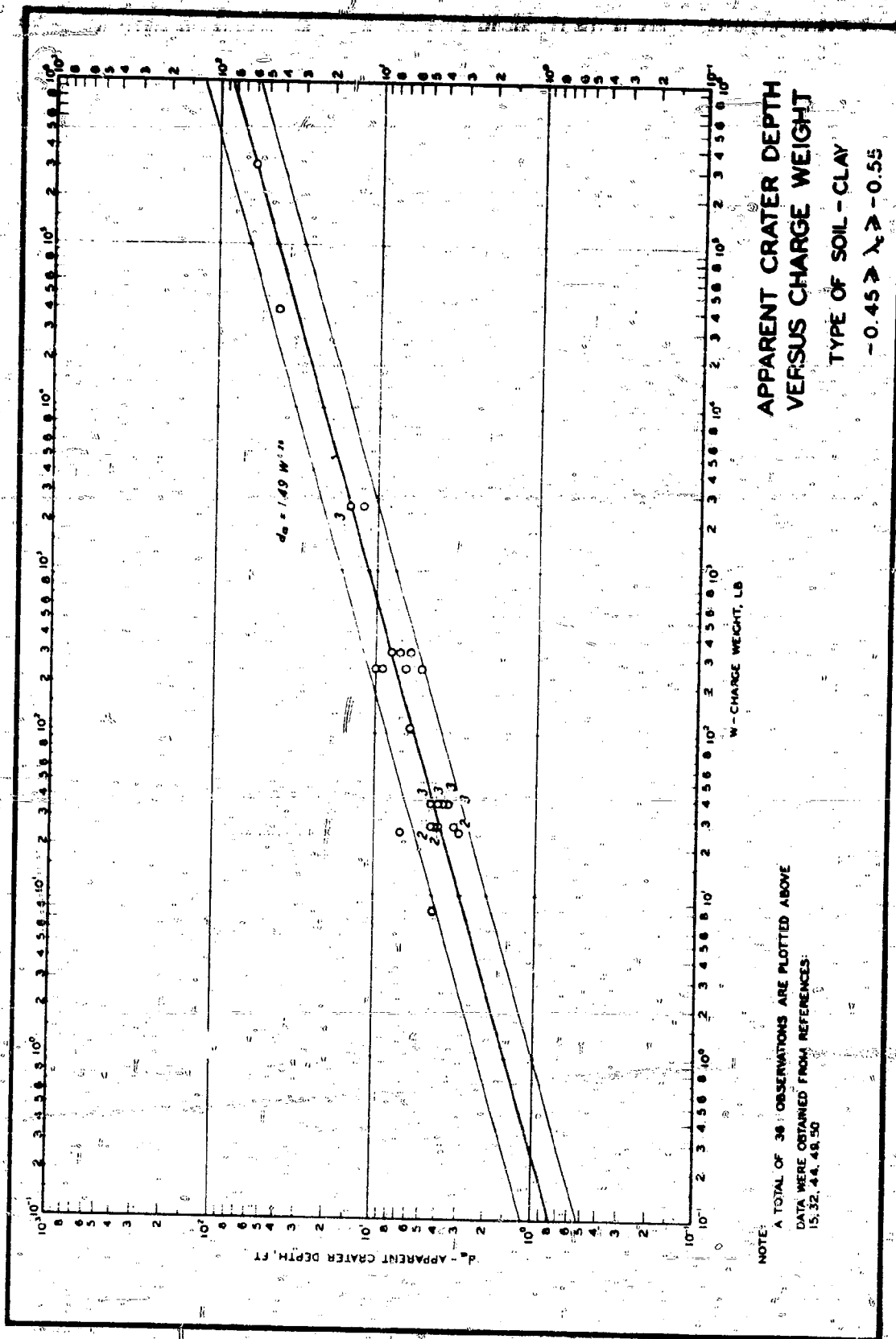
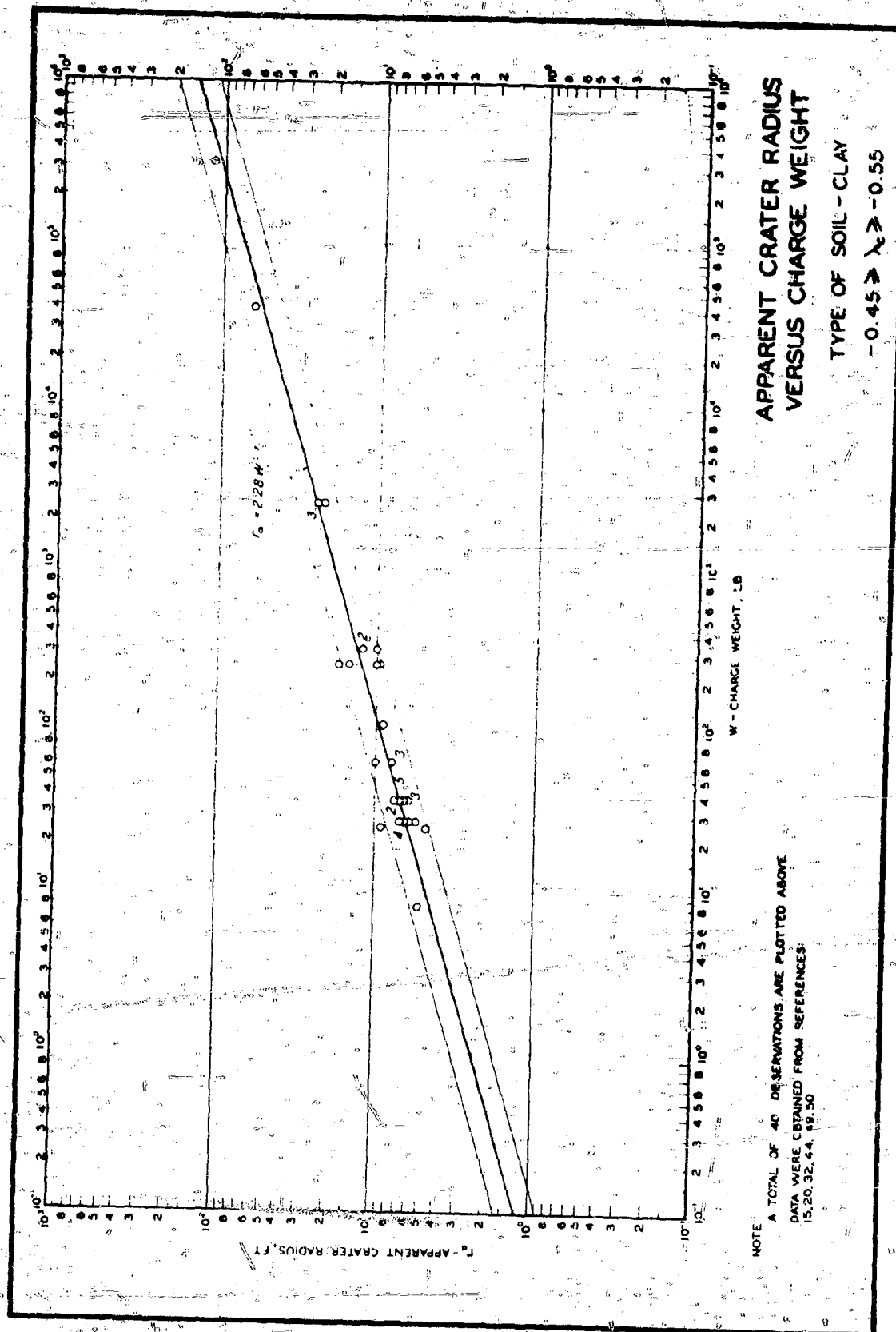
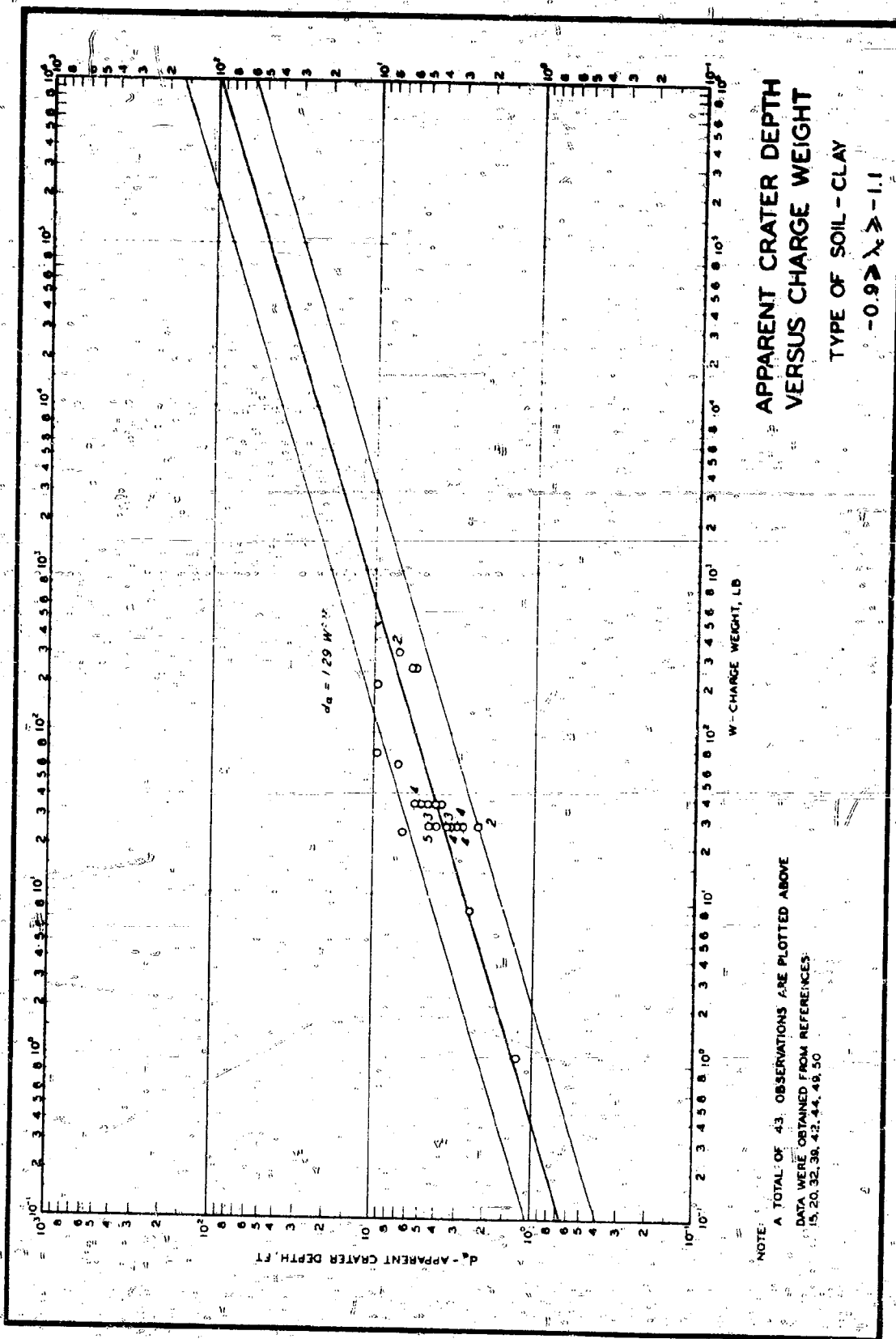
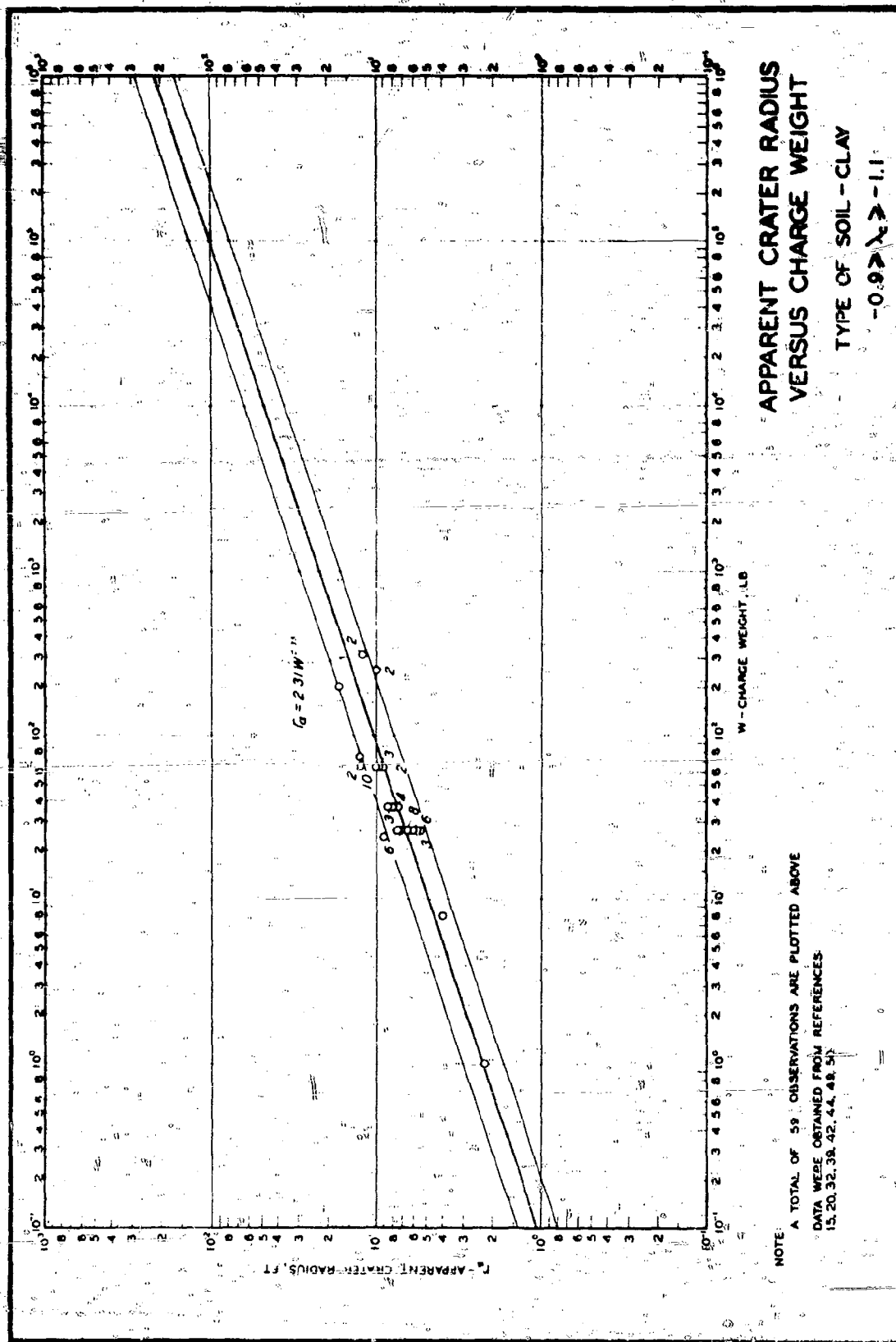


PLATE 16









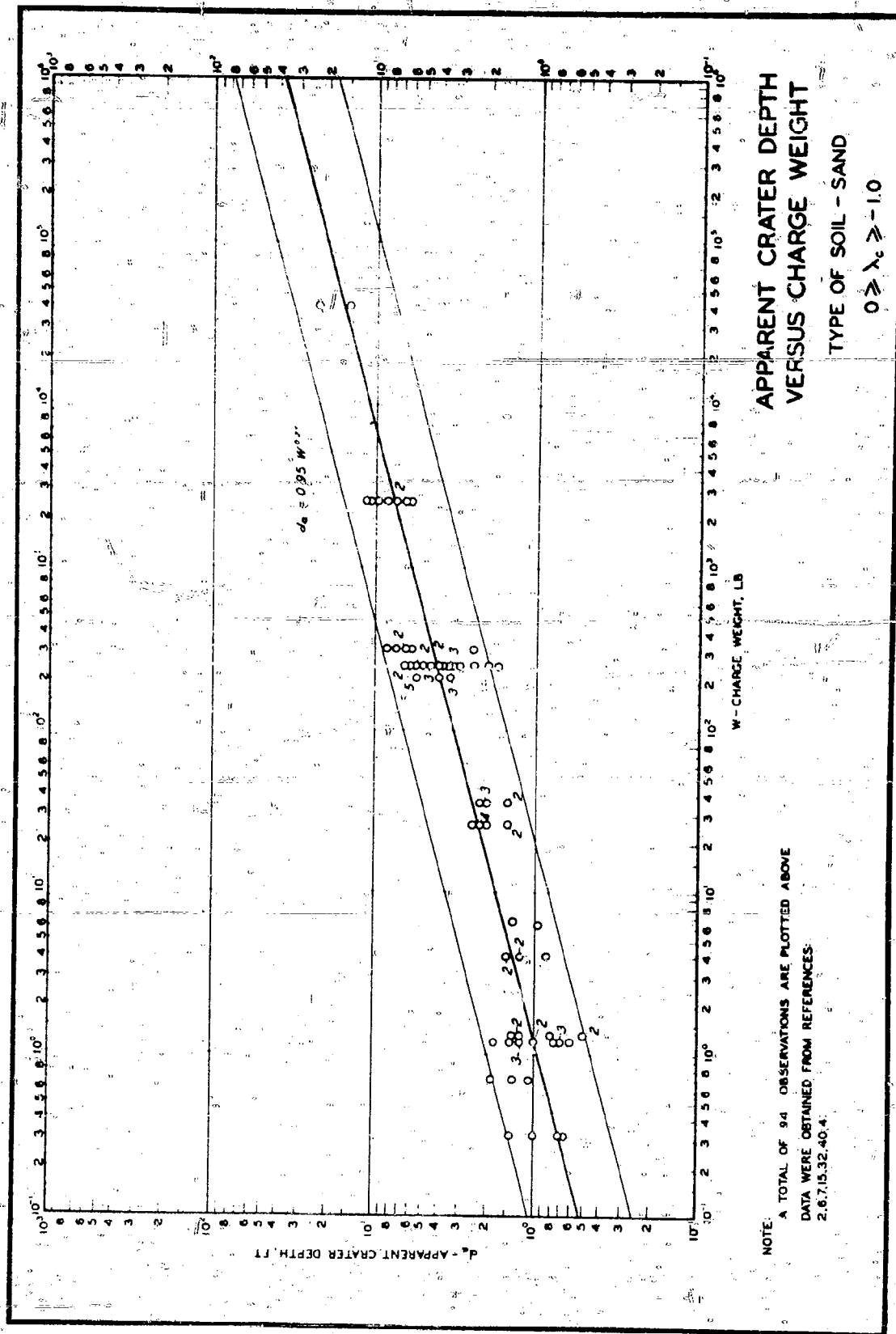
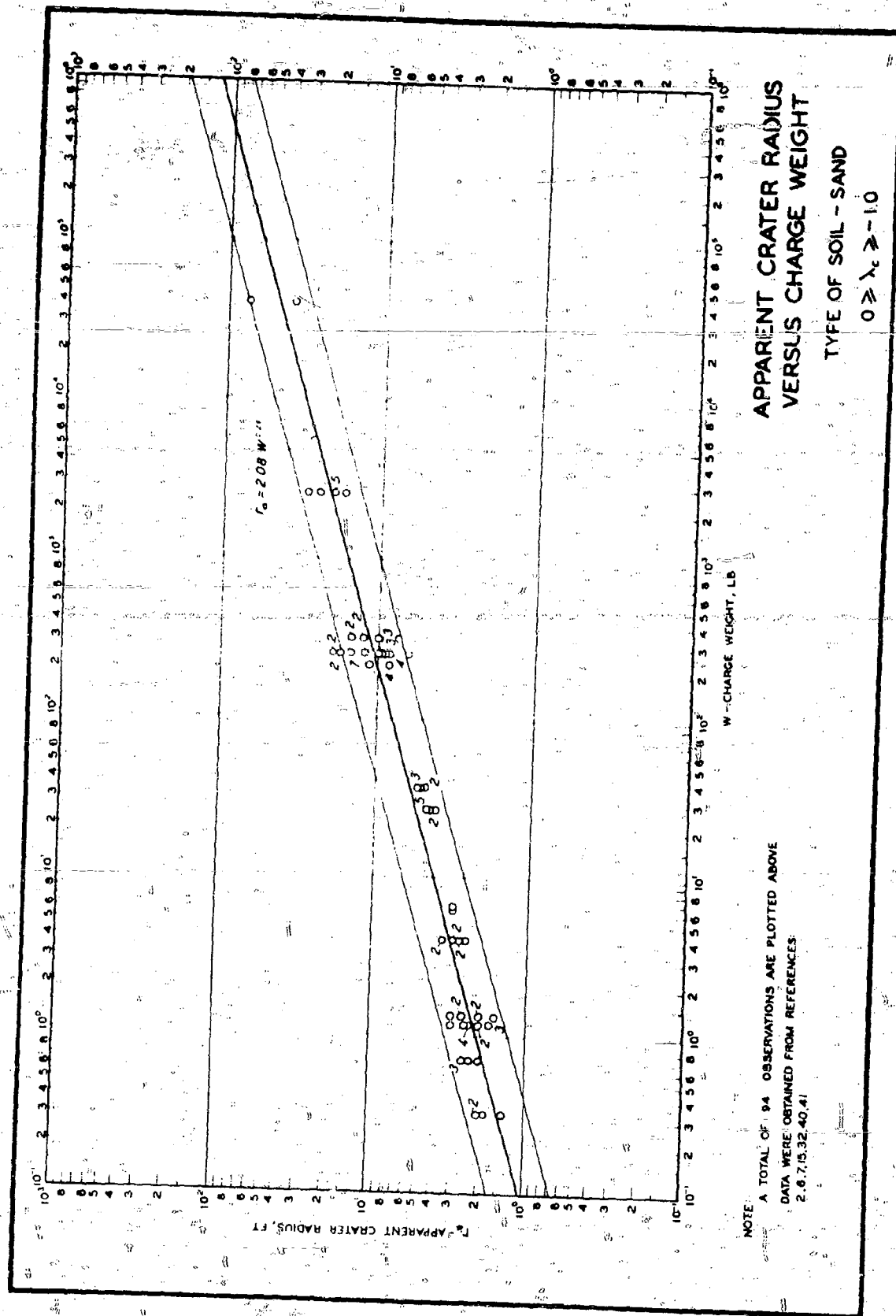
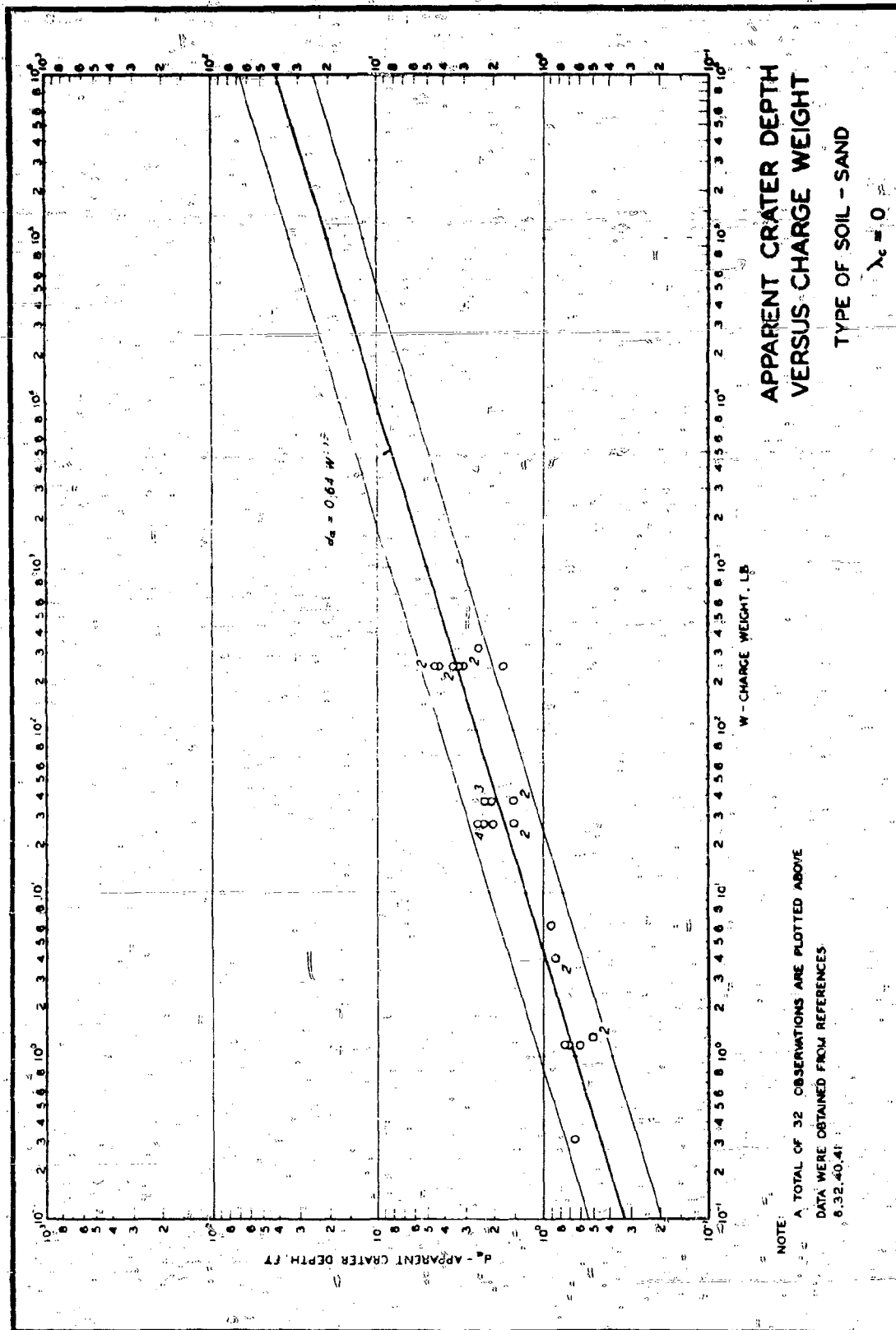
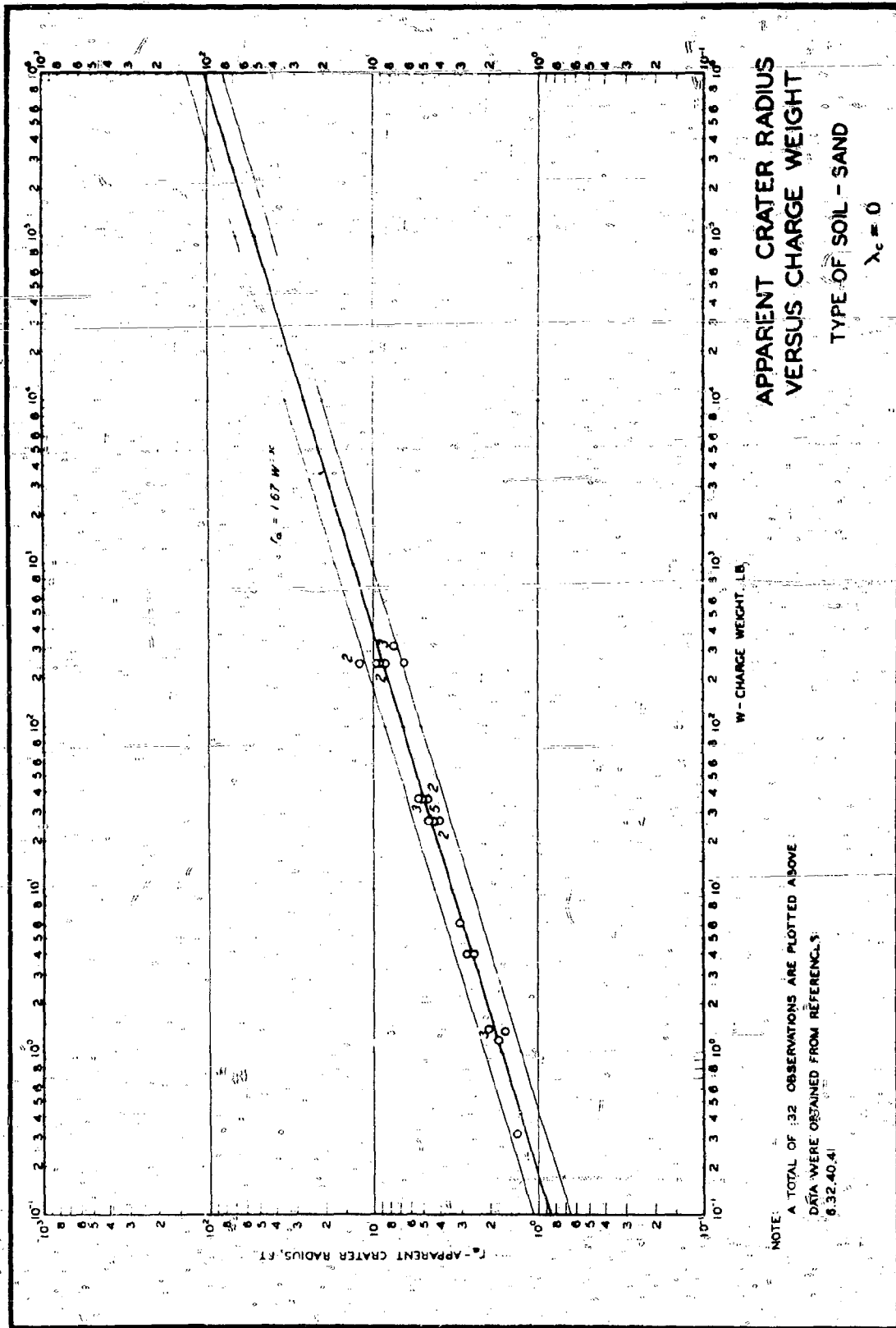
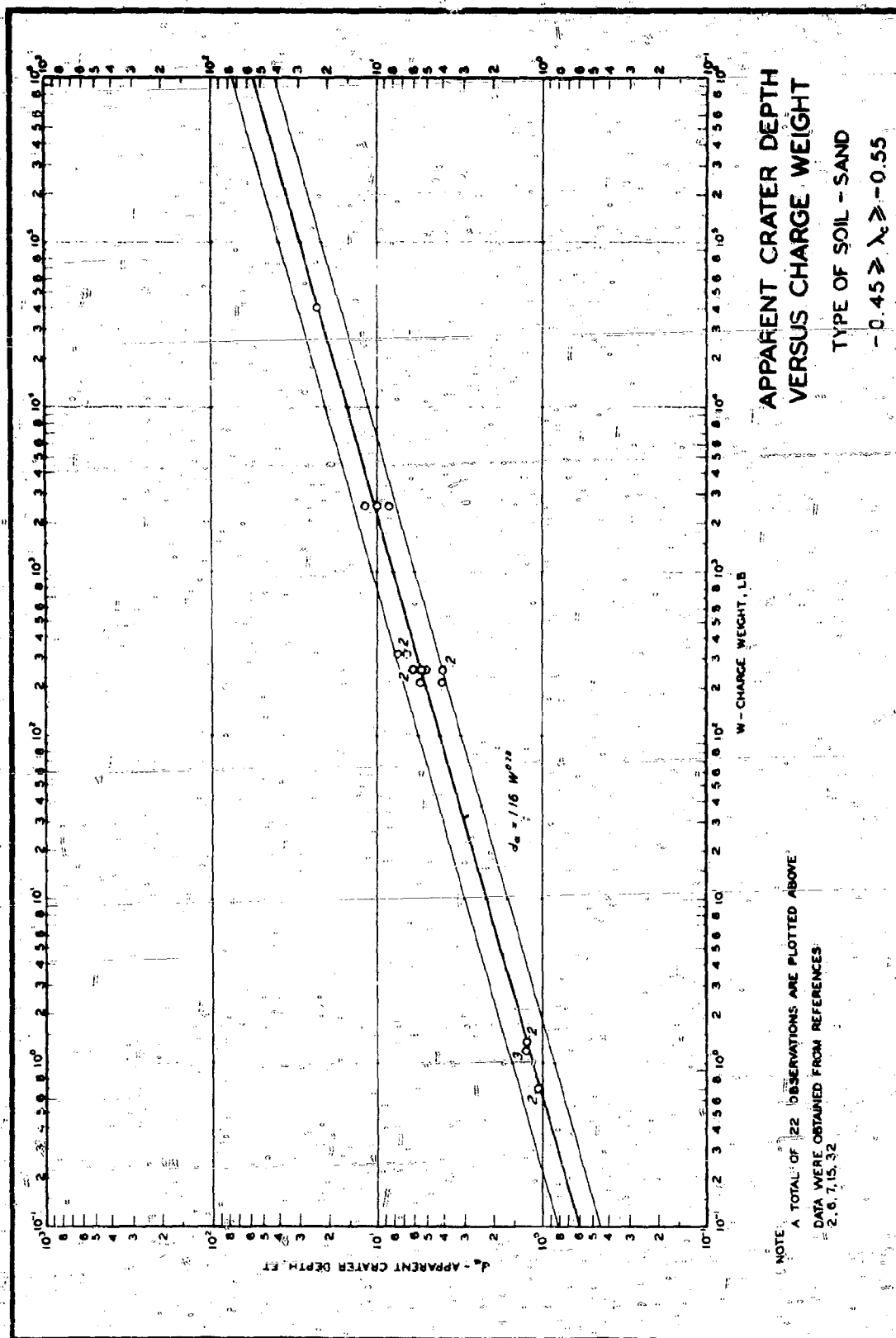


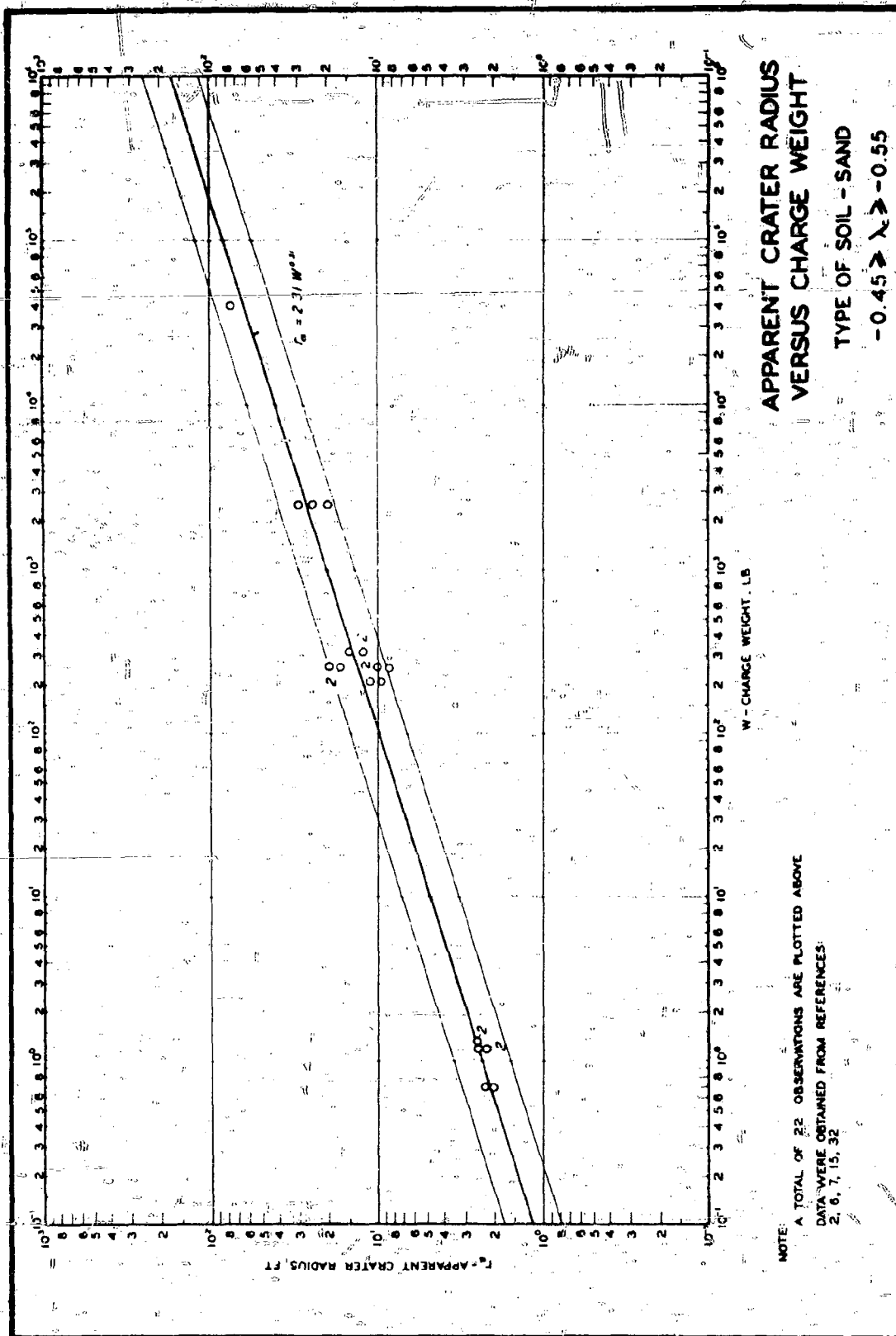
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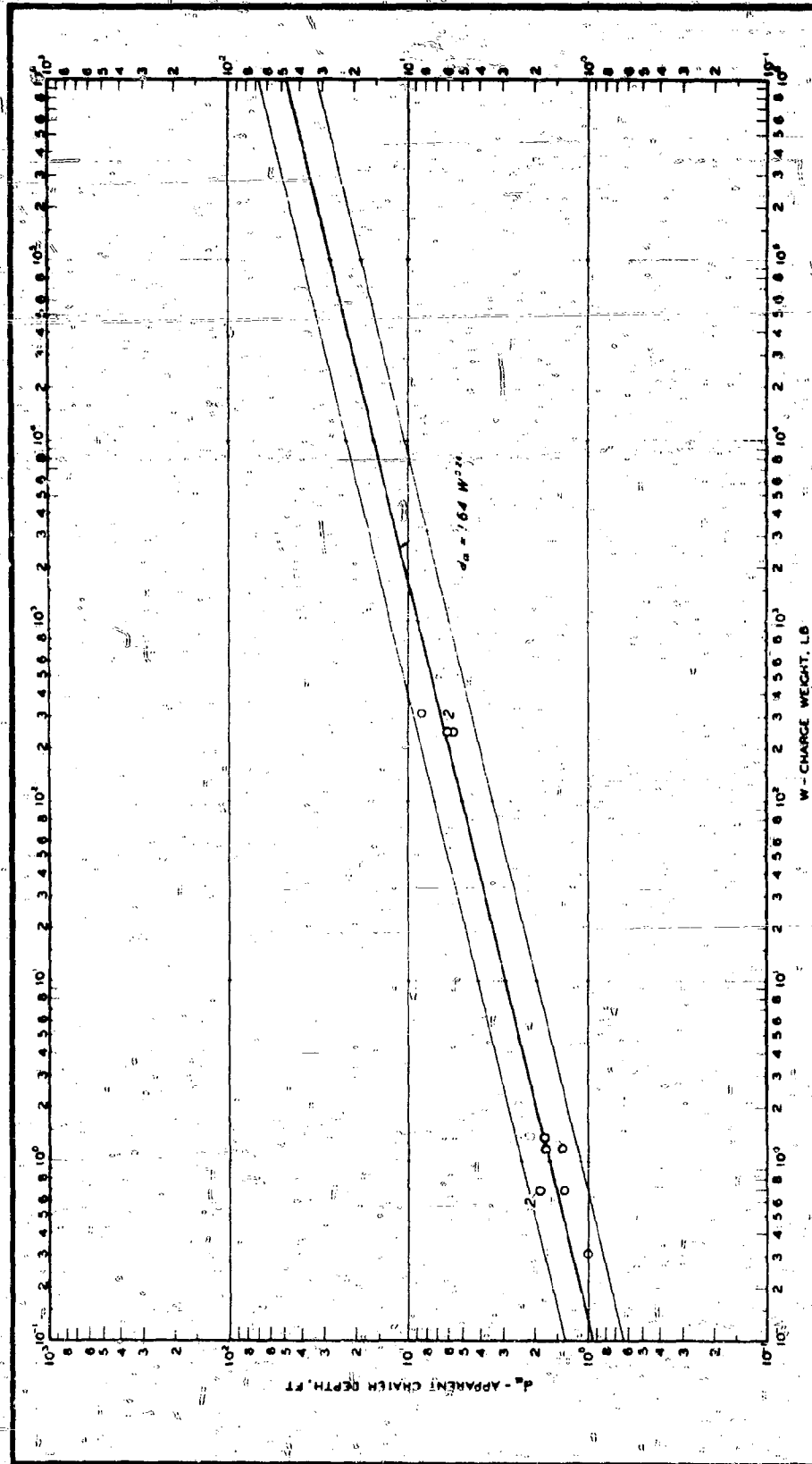










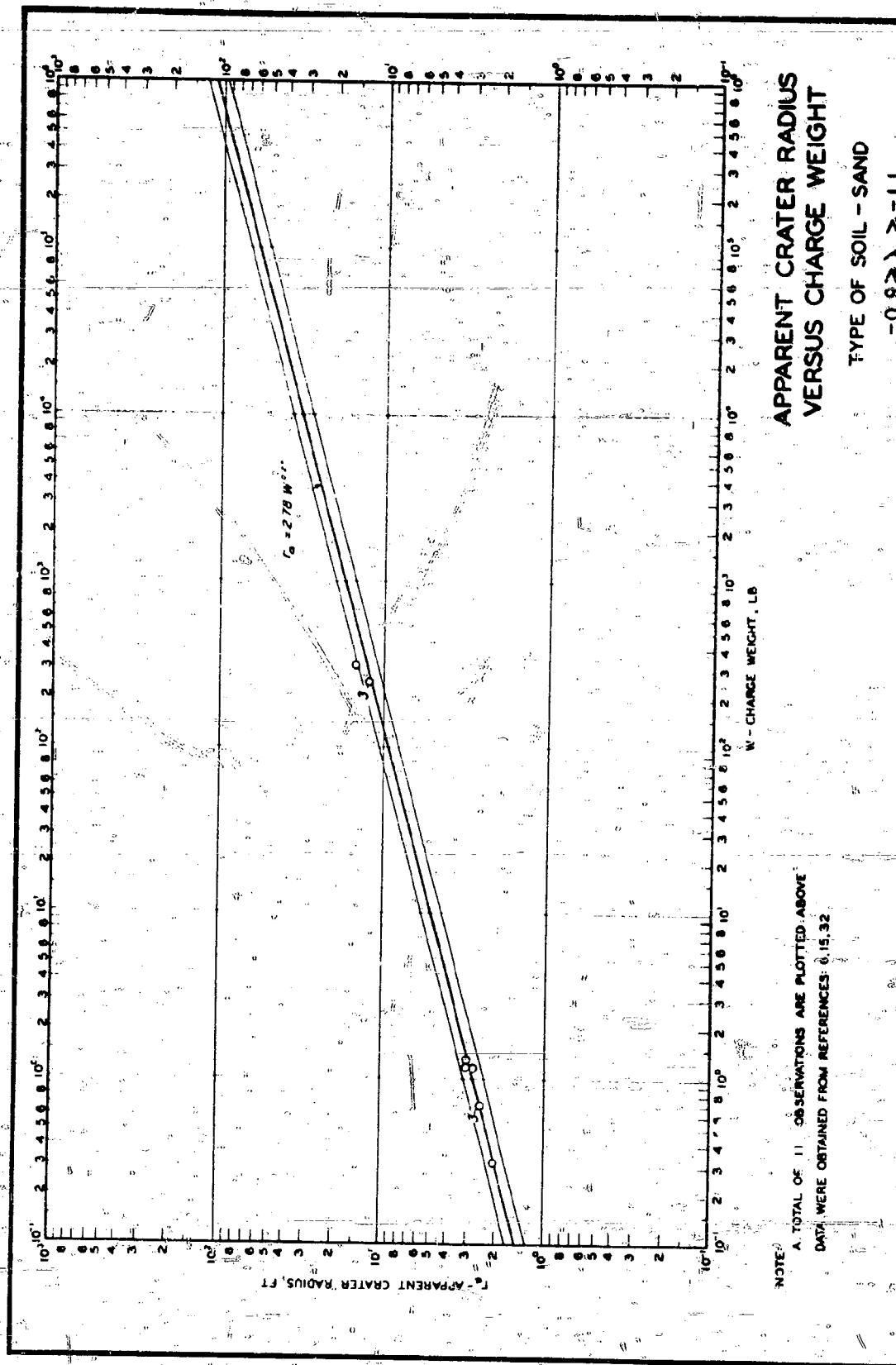


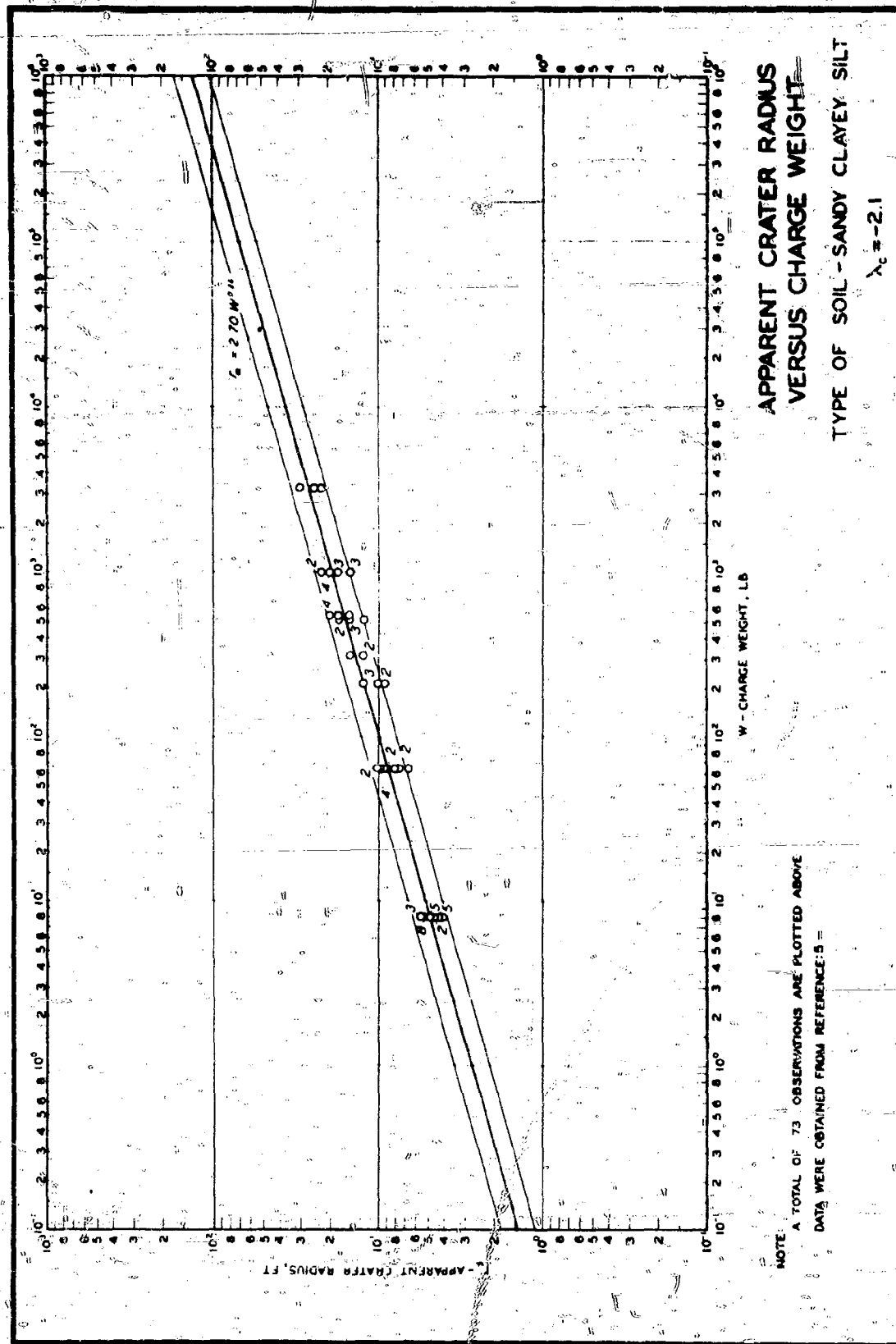
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VERSUS CHARGE WEIGHT

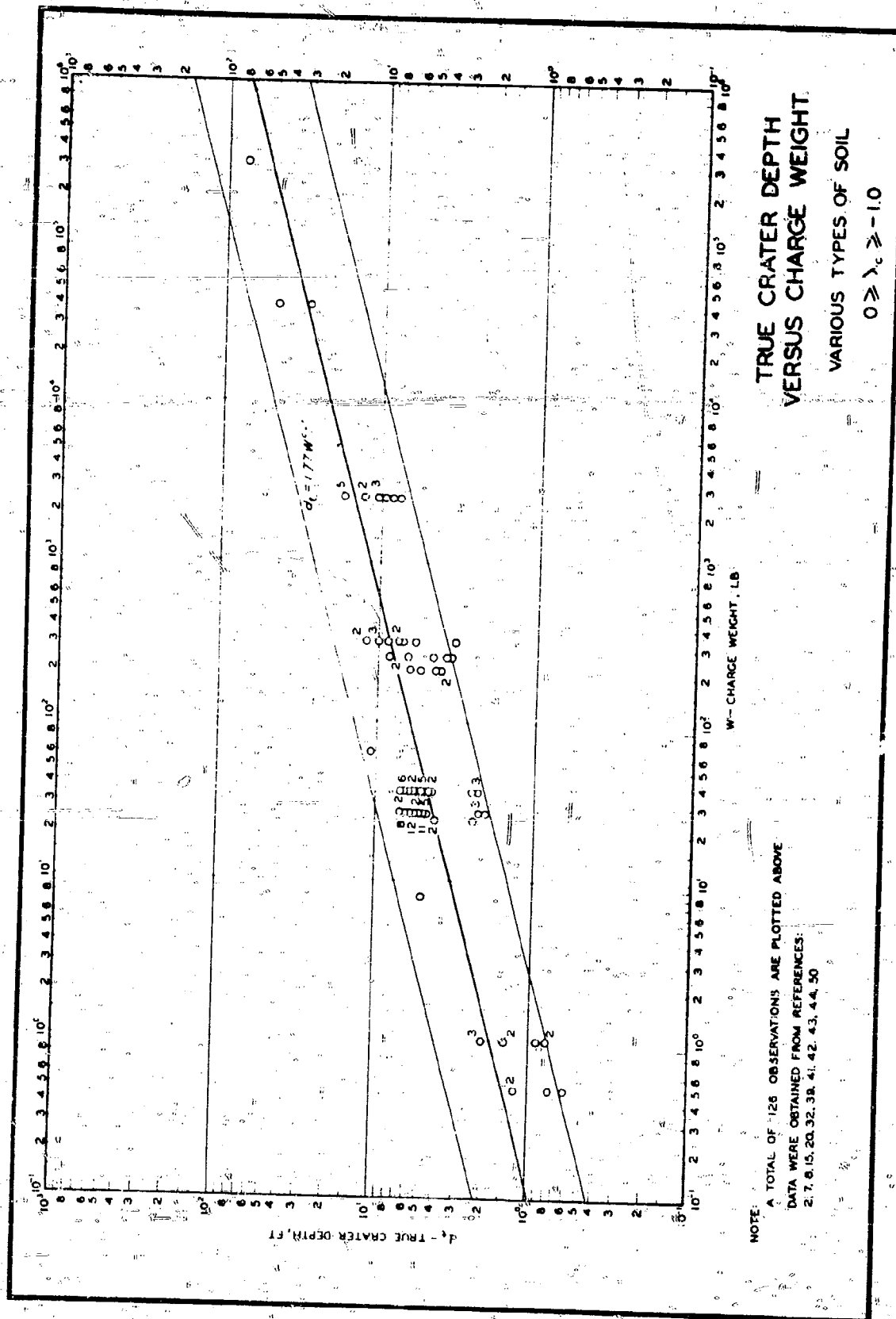
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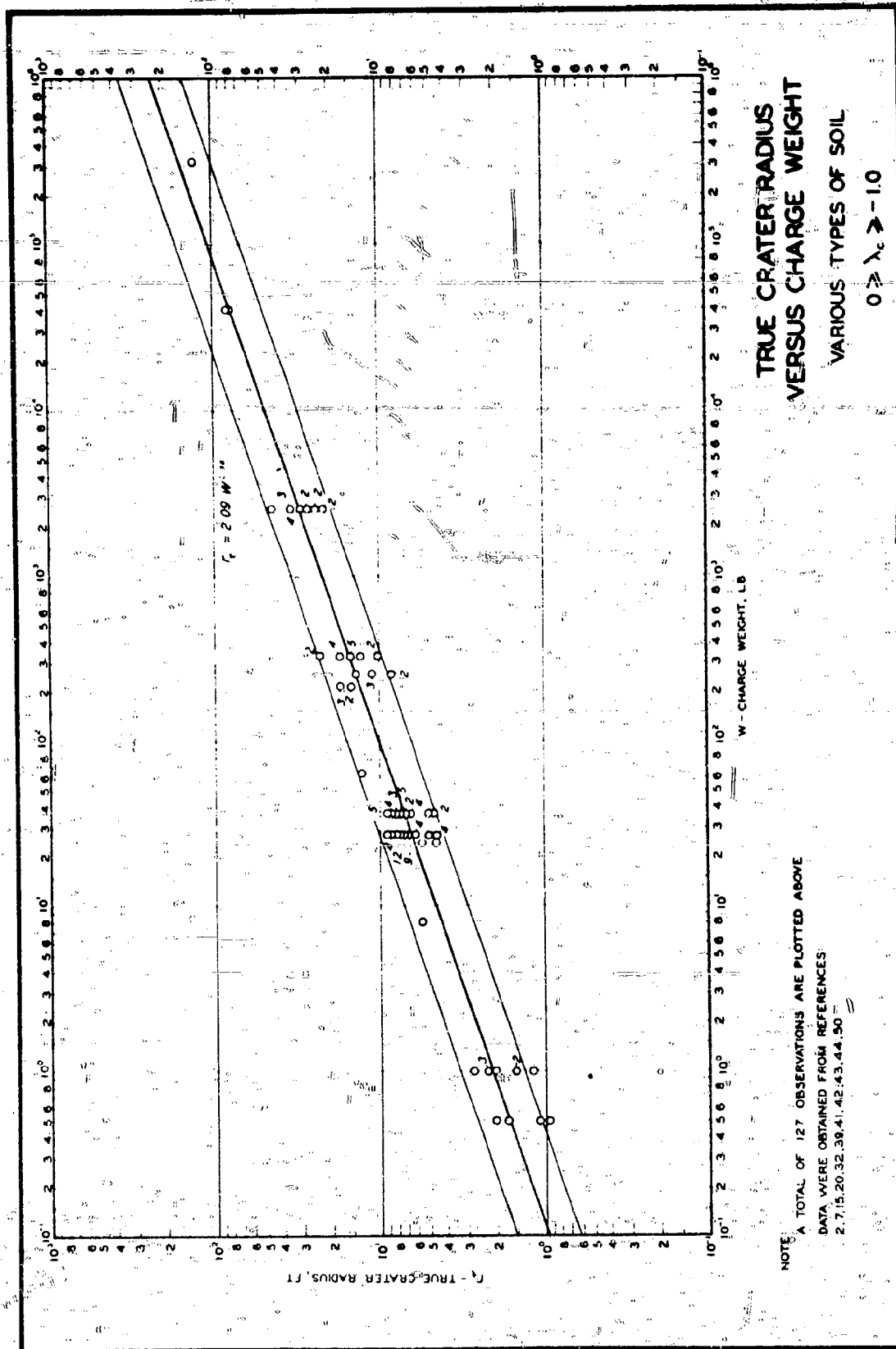
-0.92 $\lambda_c \geq -1.1$

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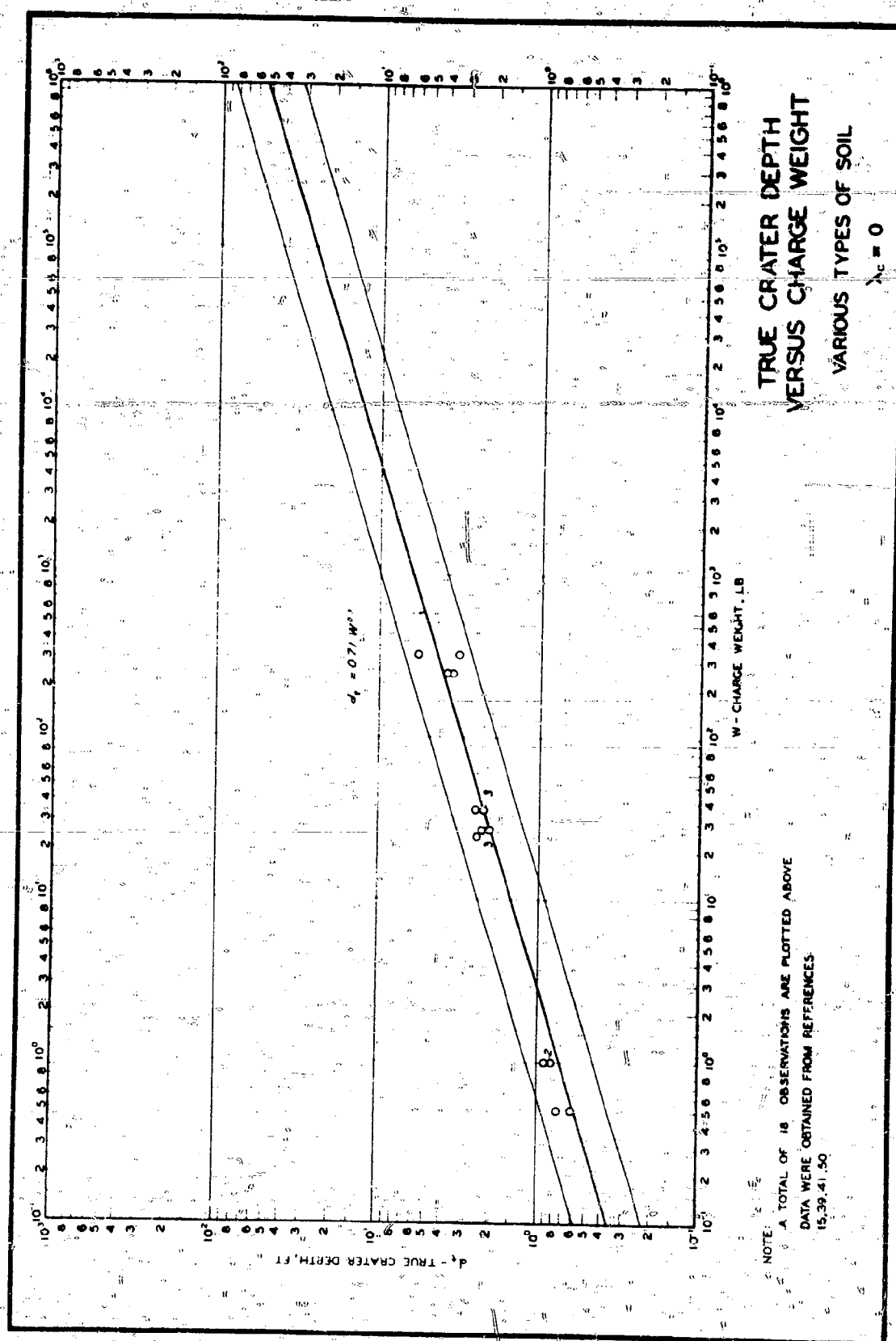


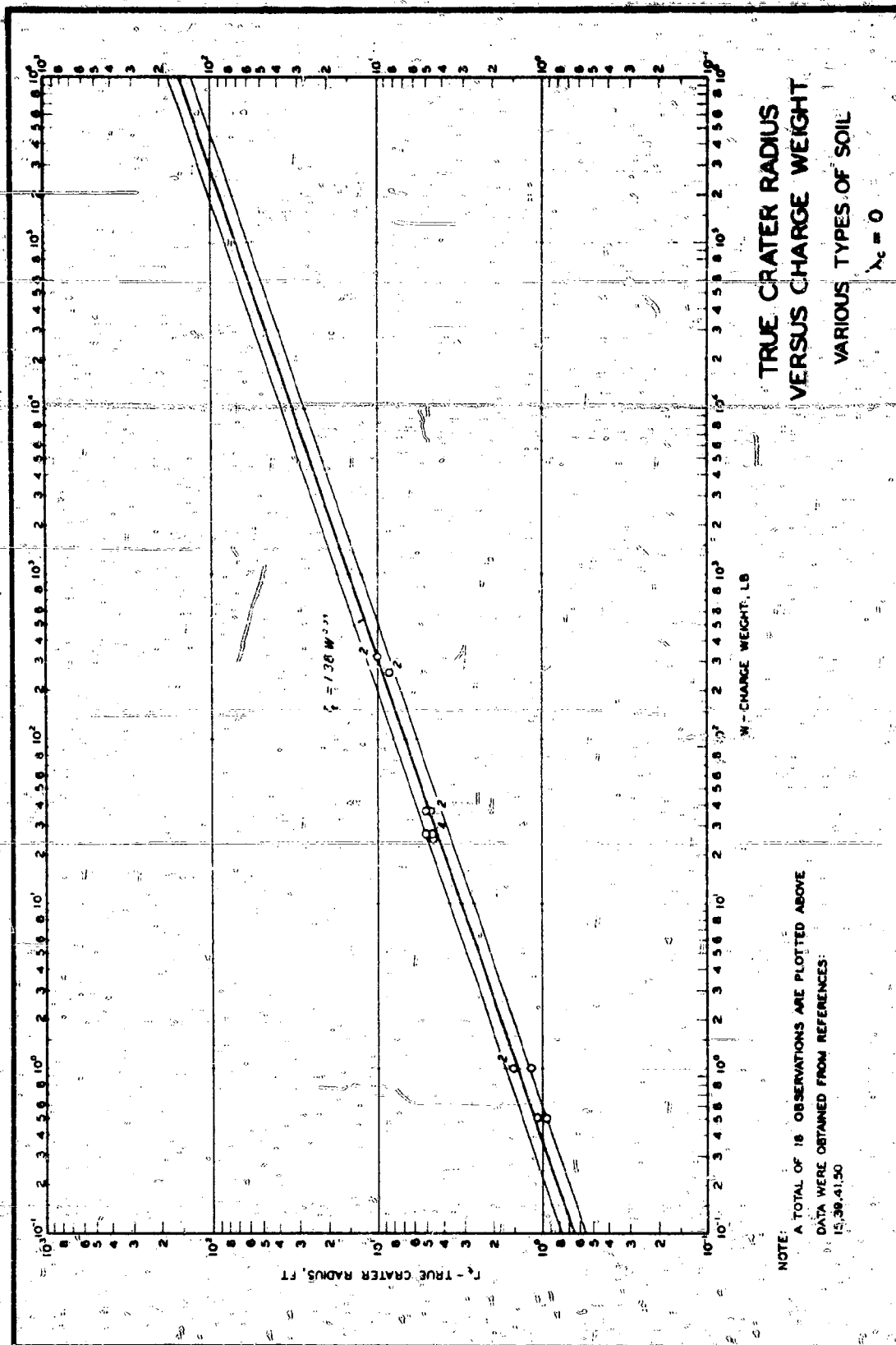


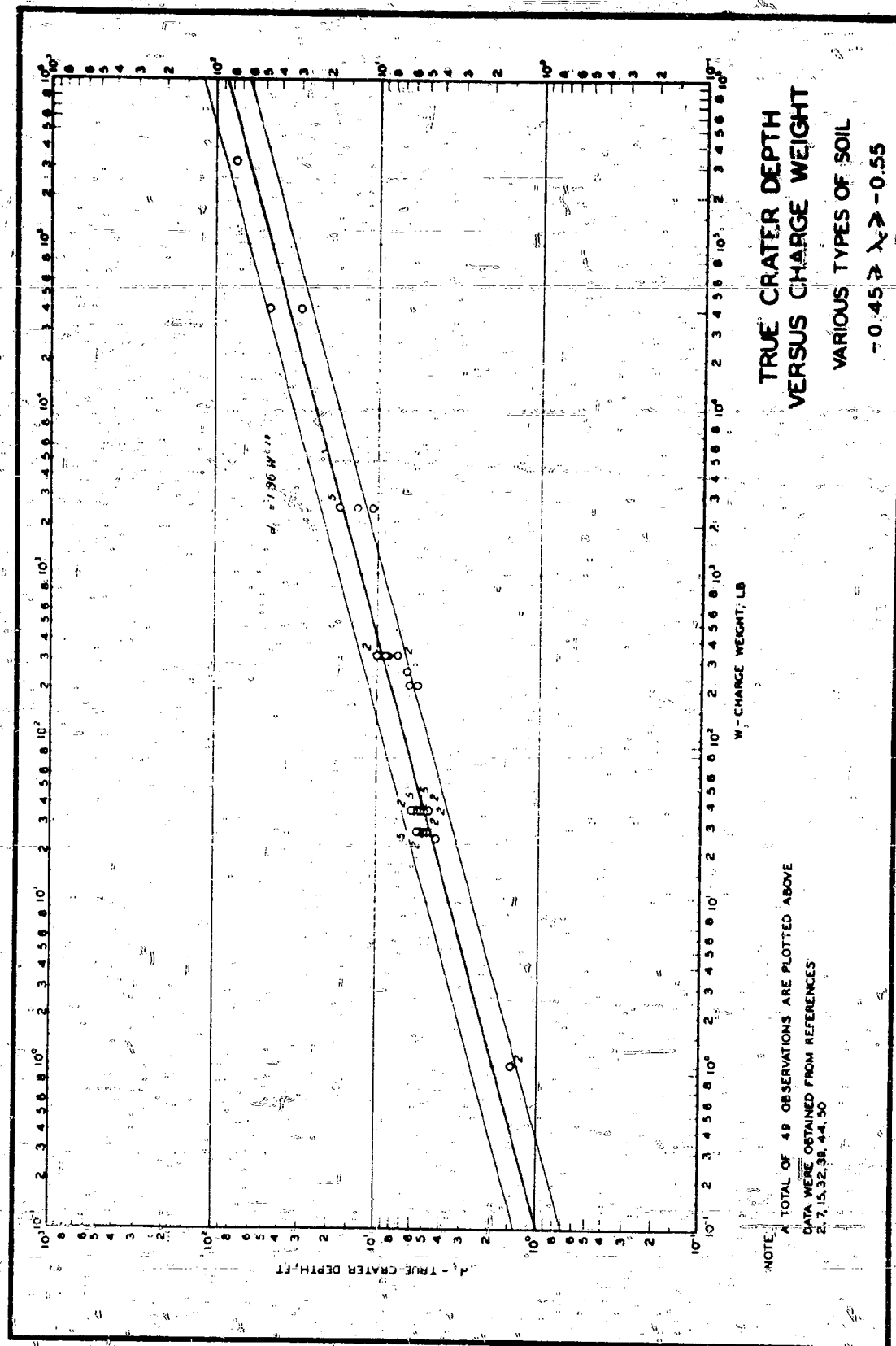


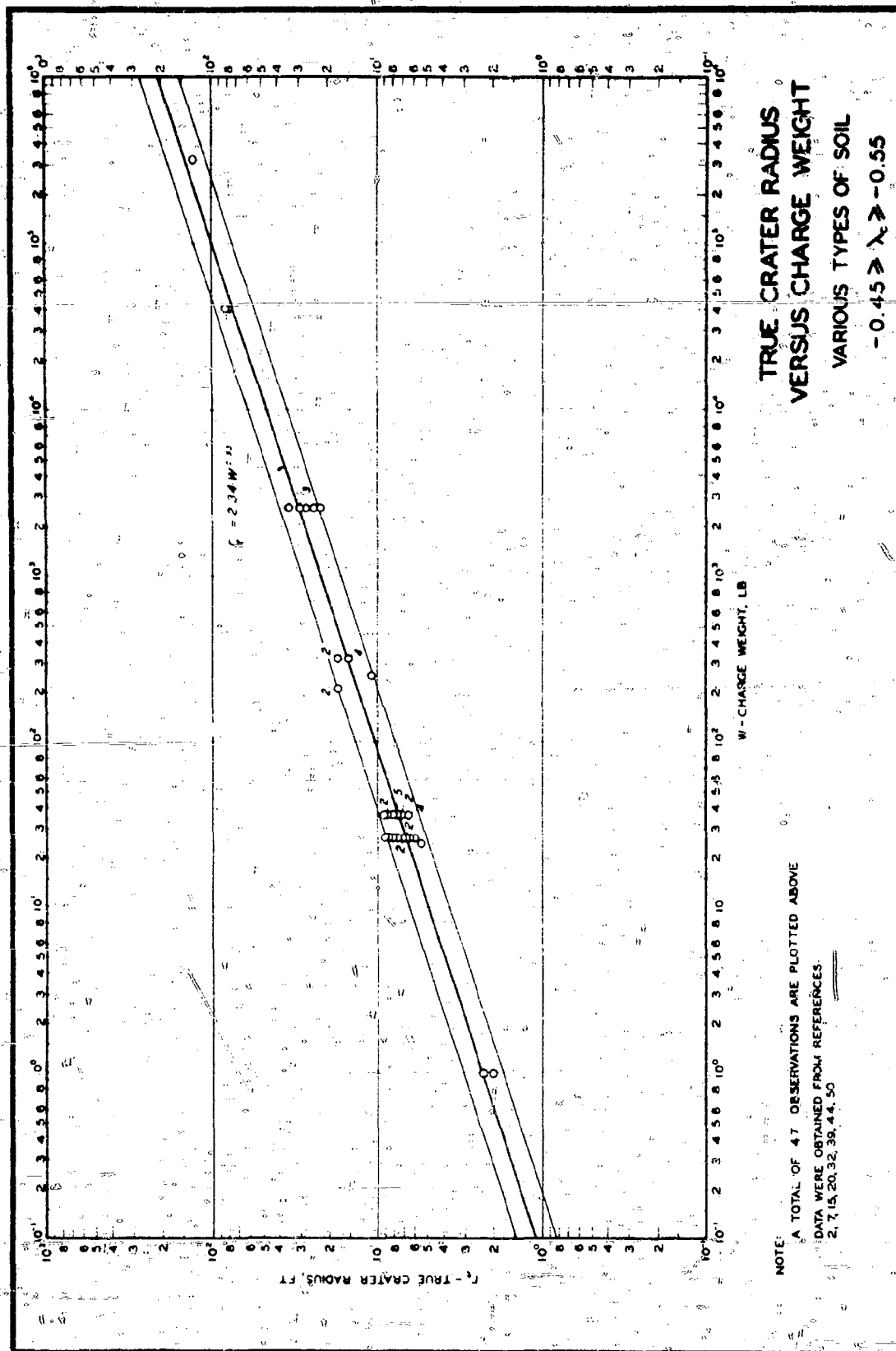


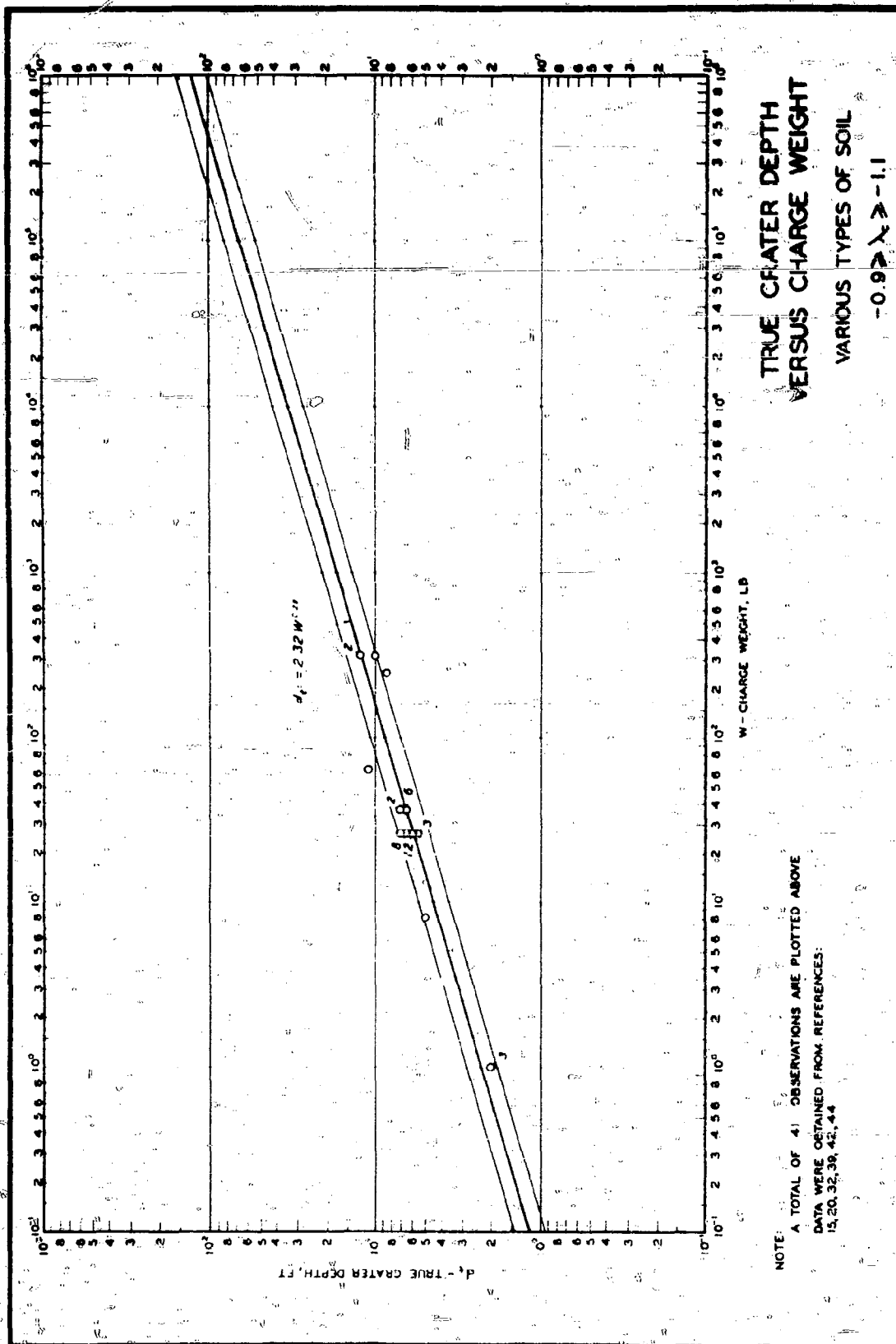
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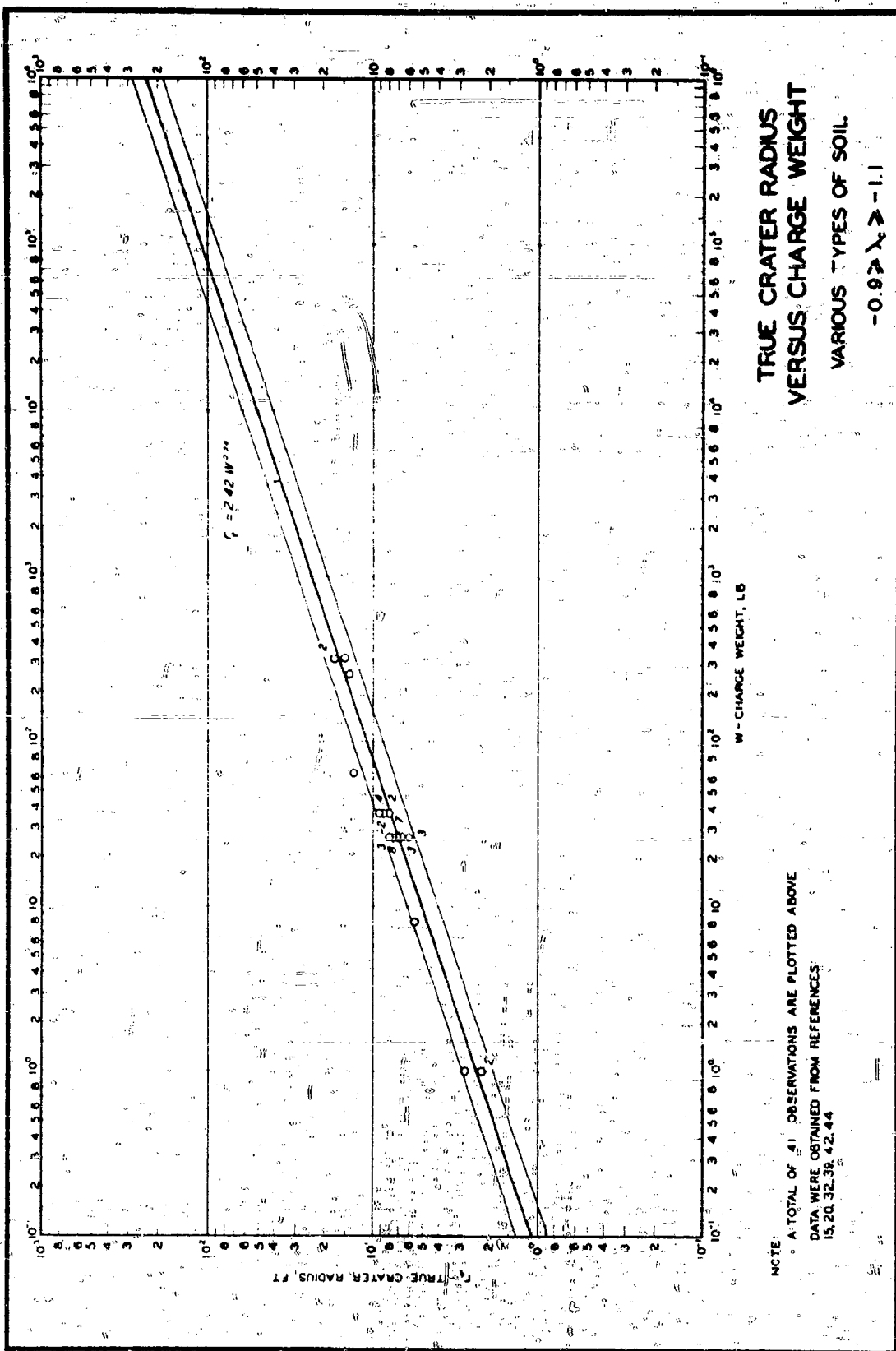


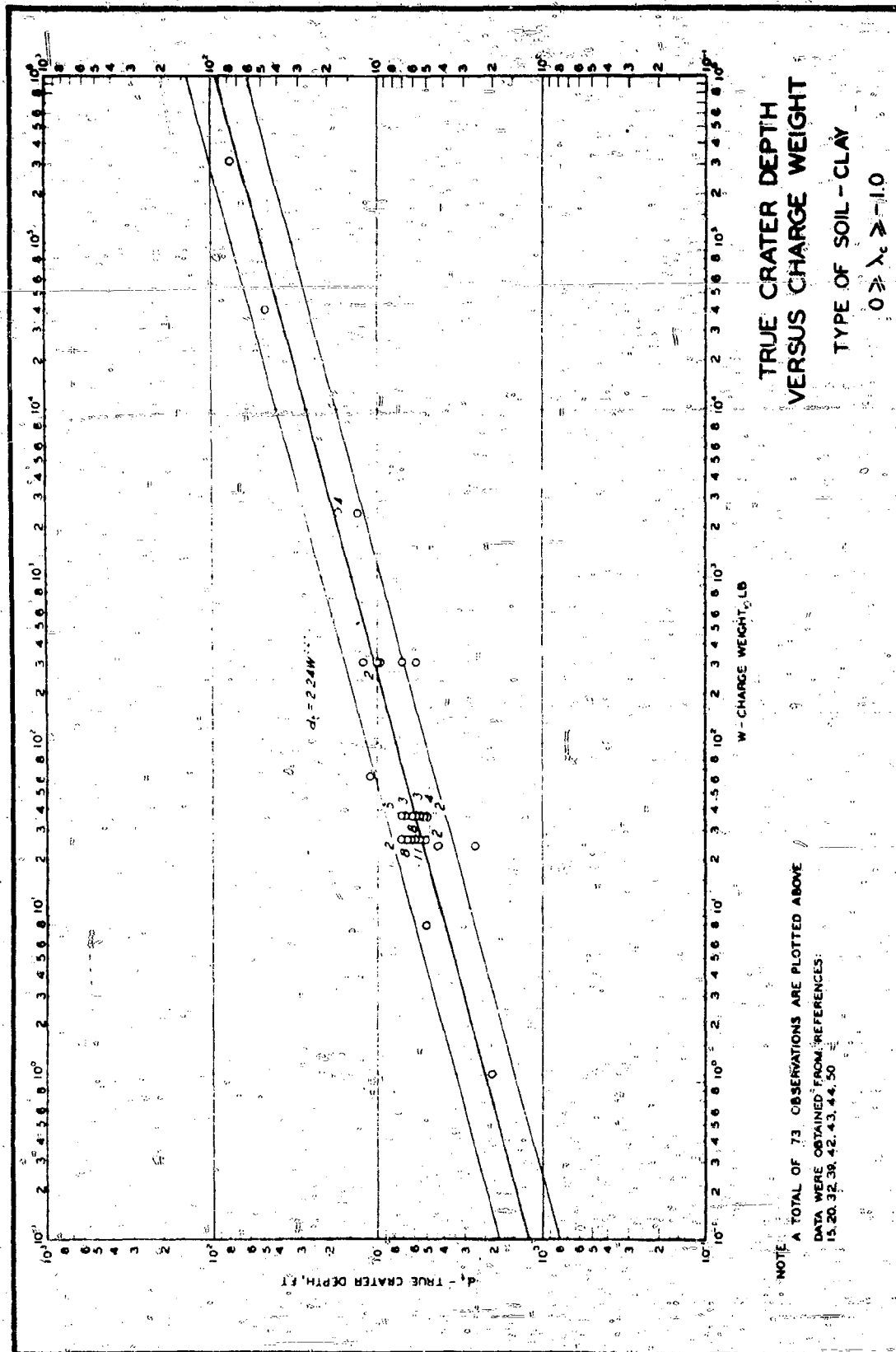


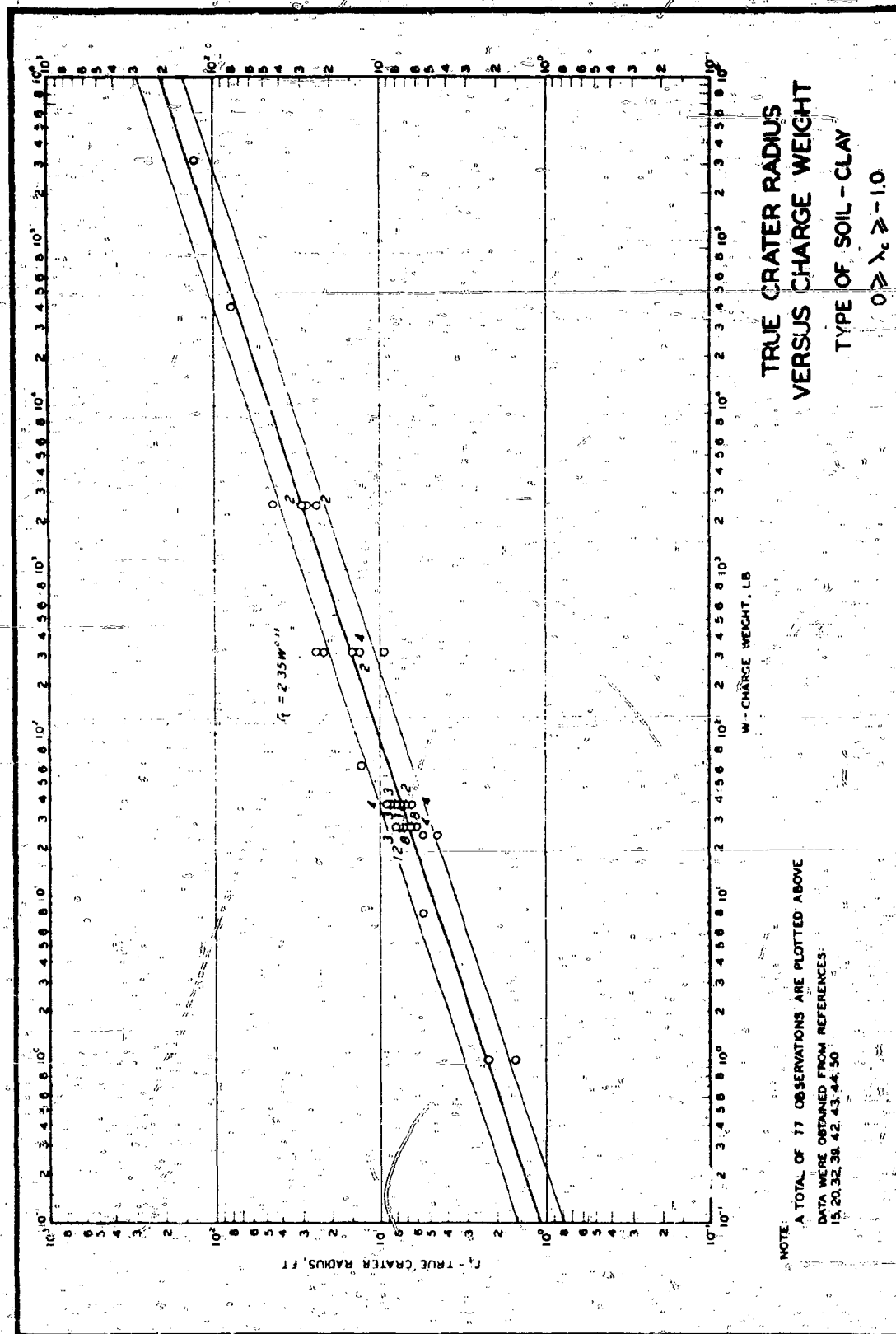


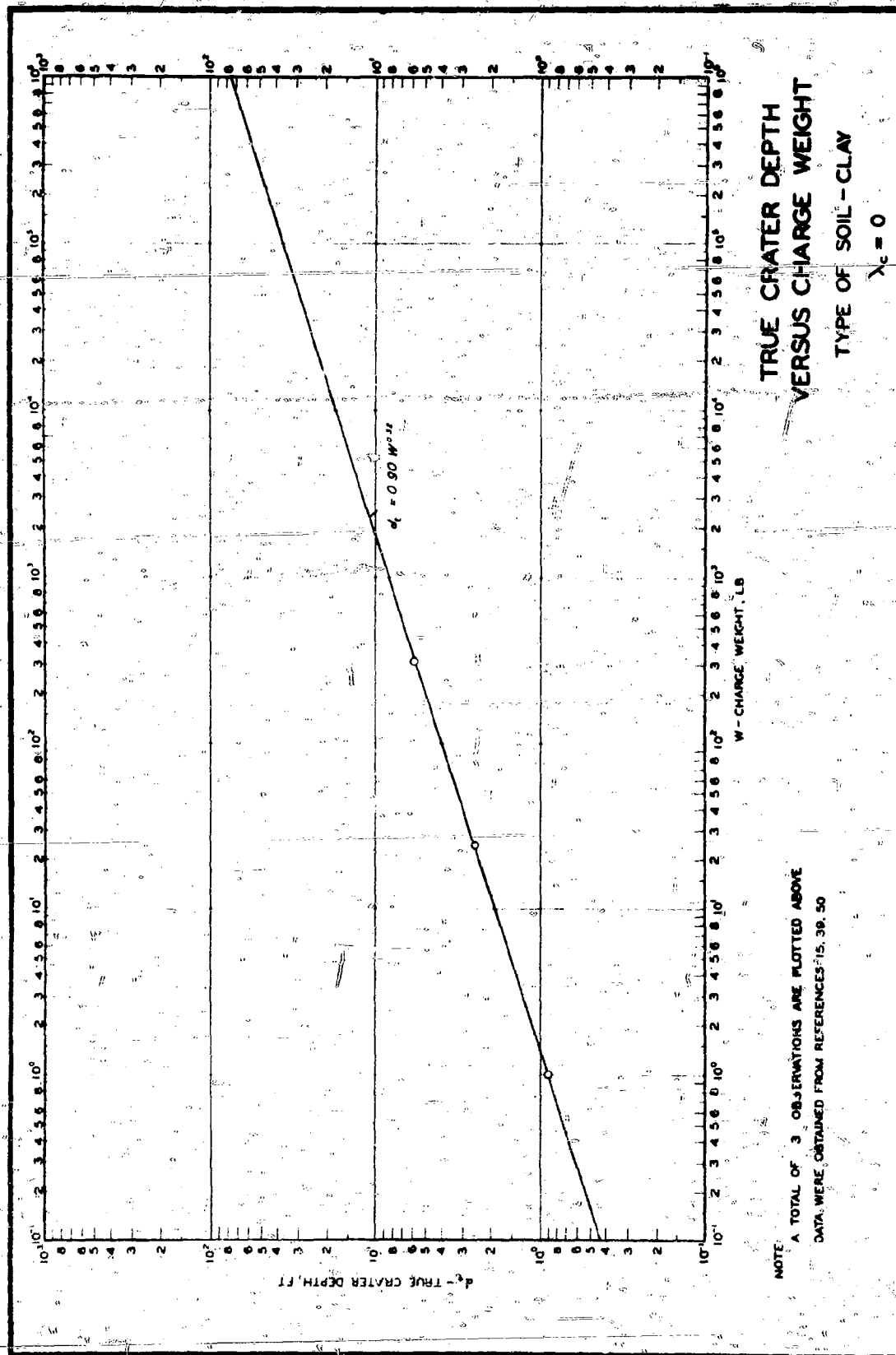


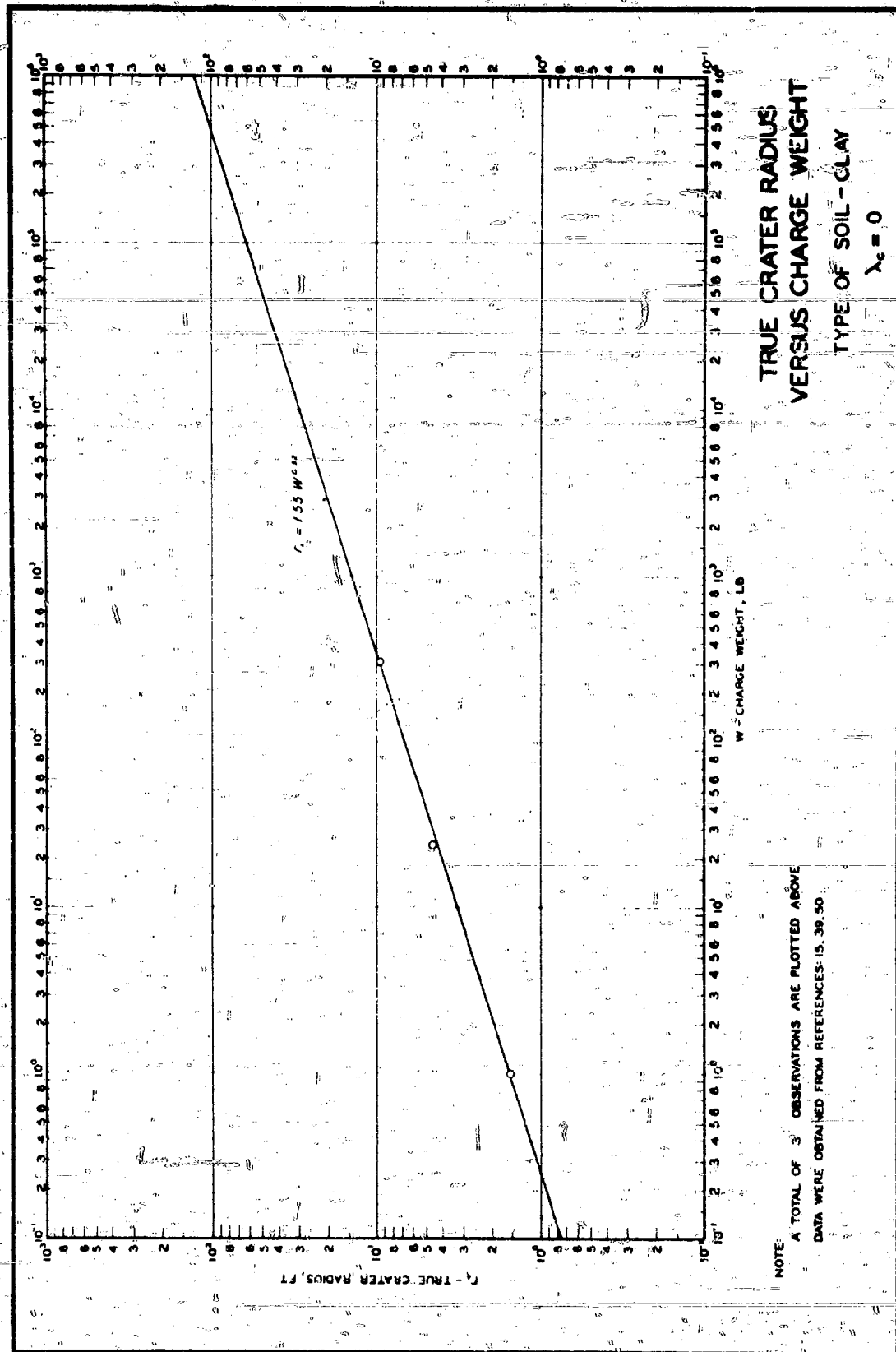


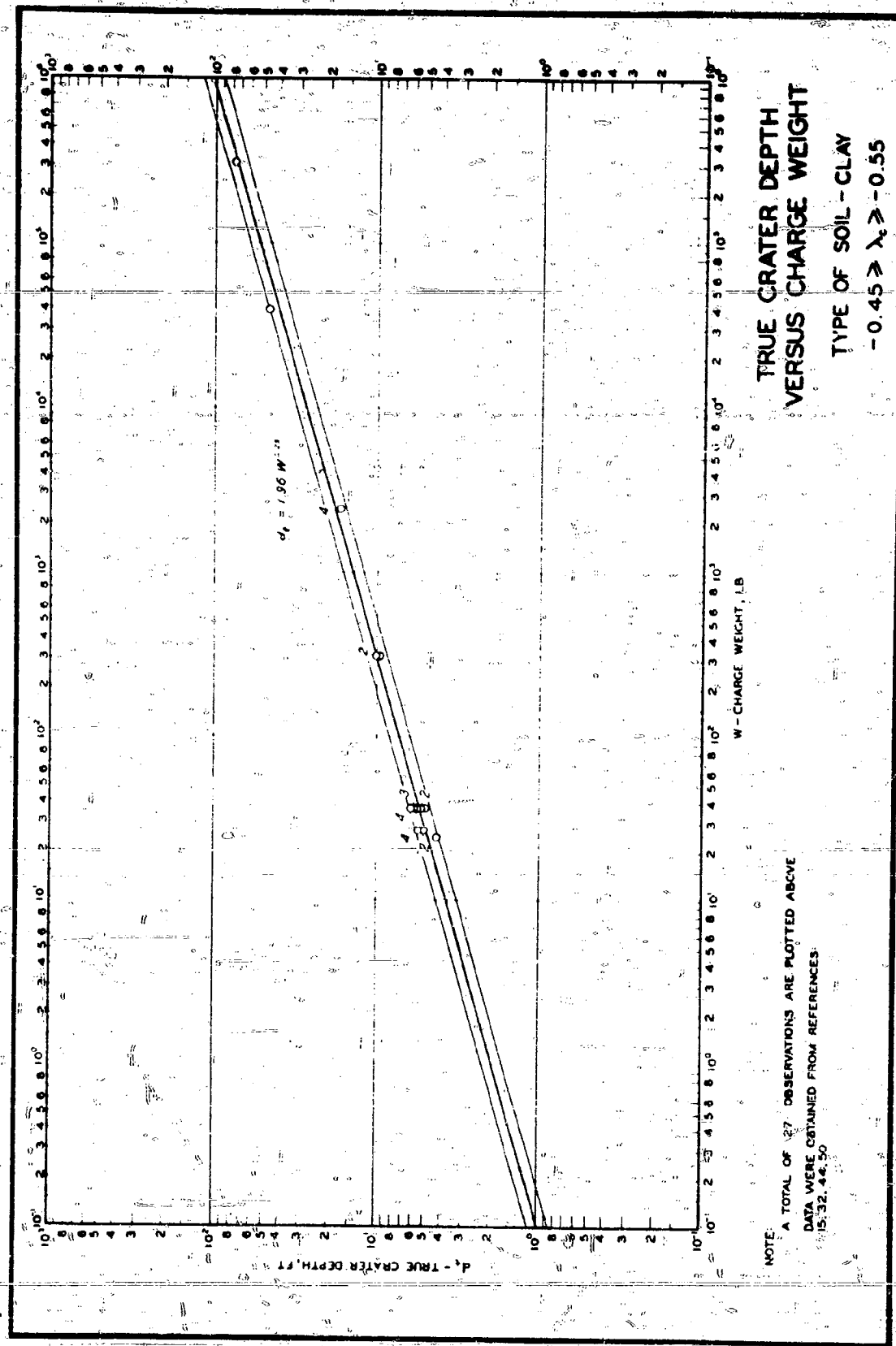


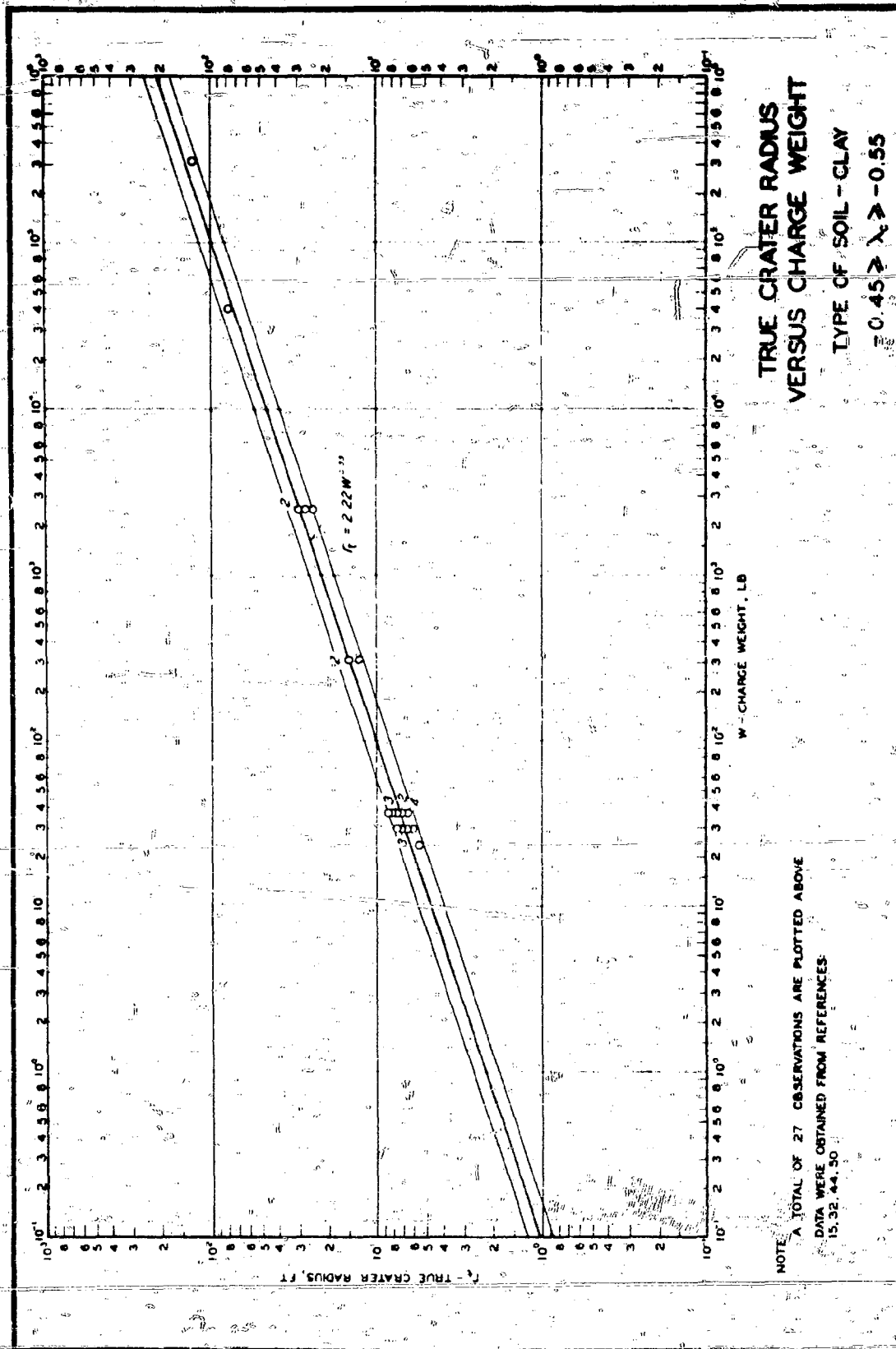


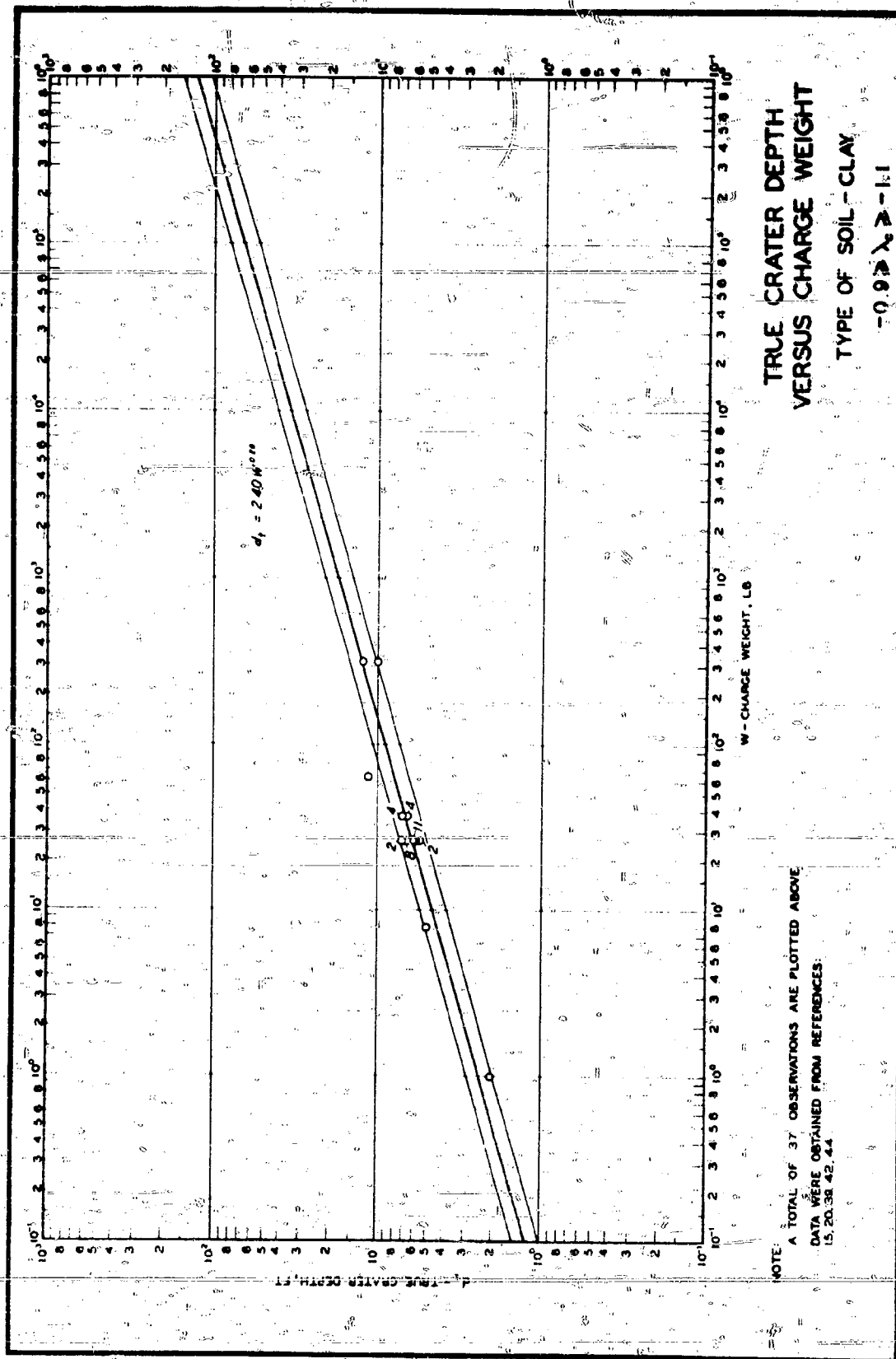


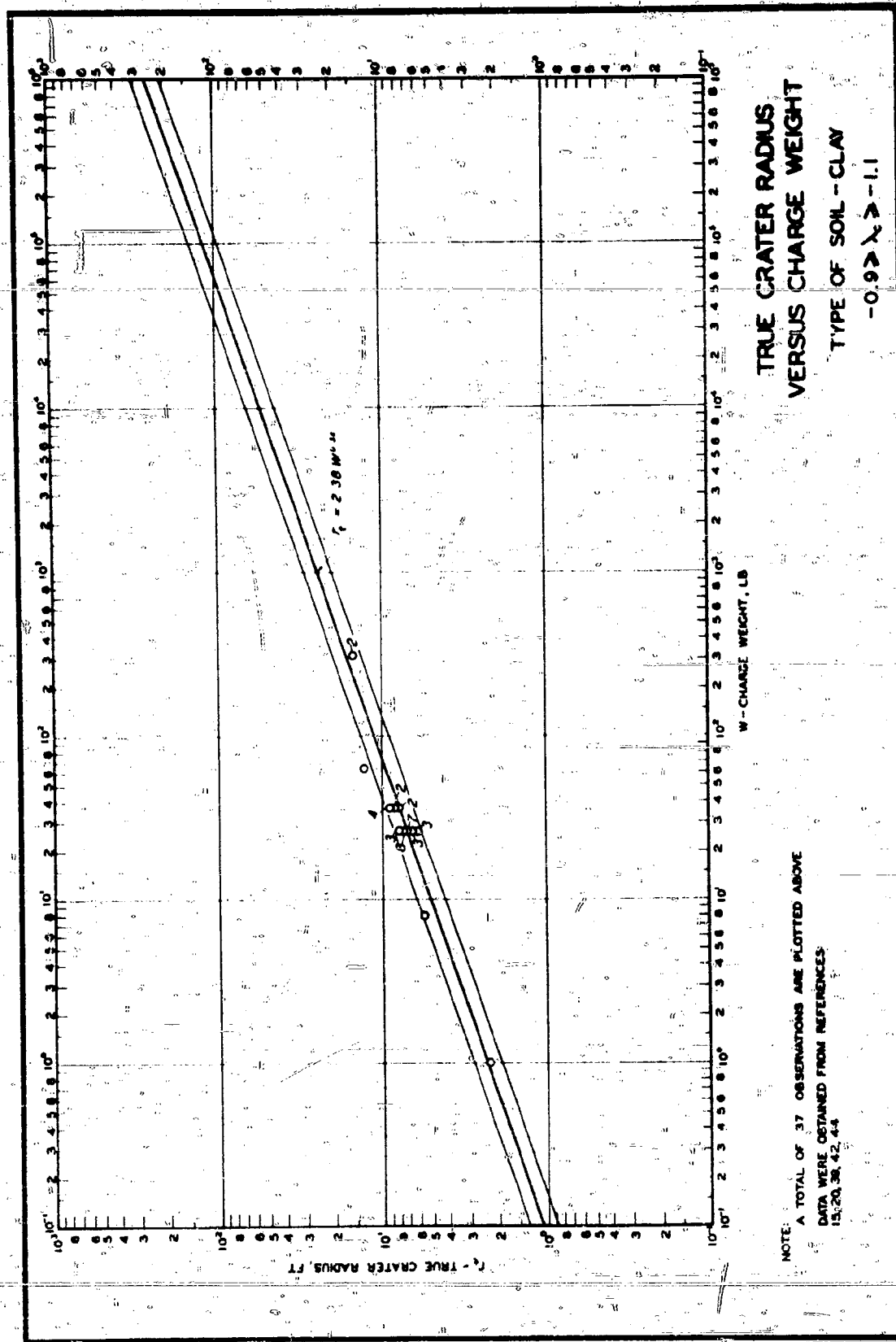


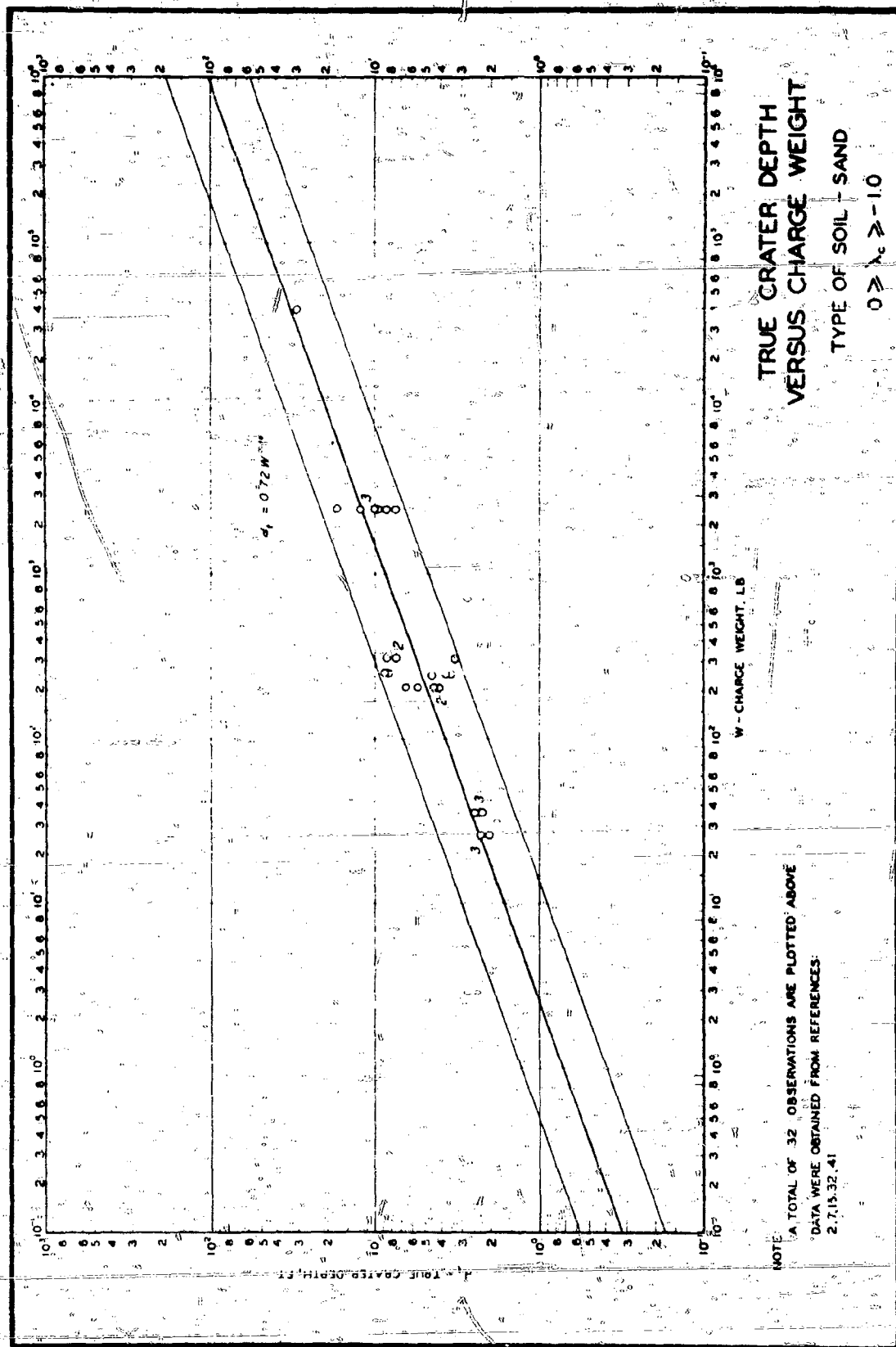












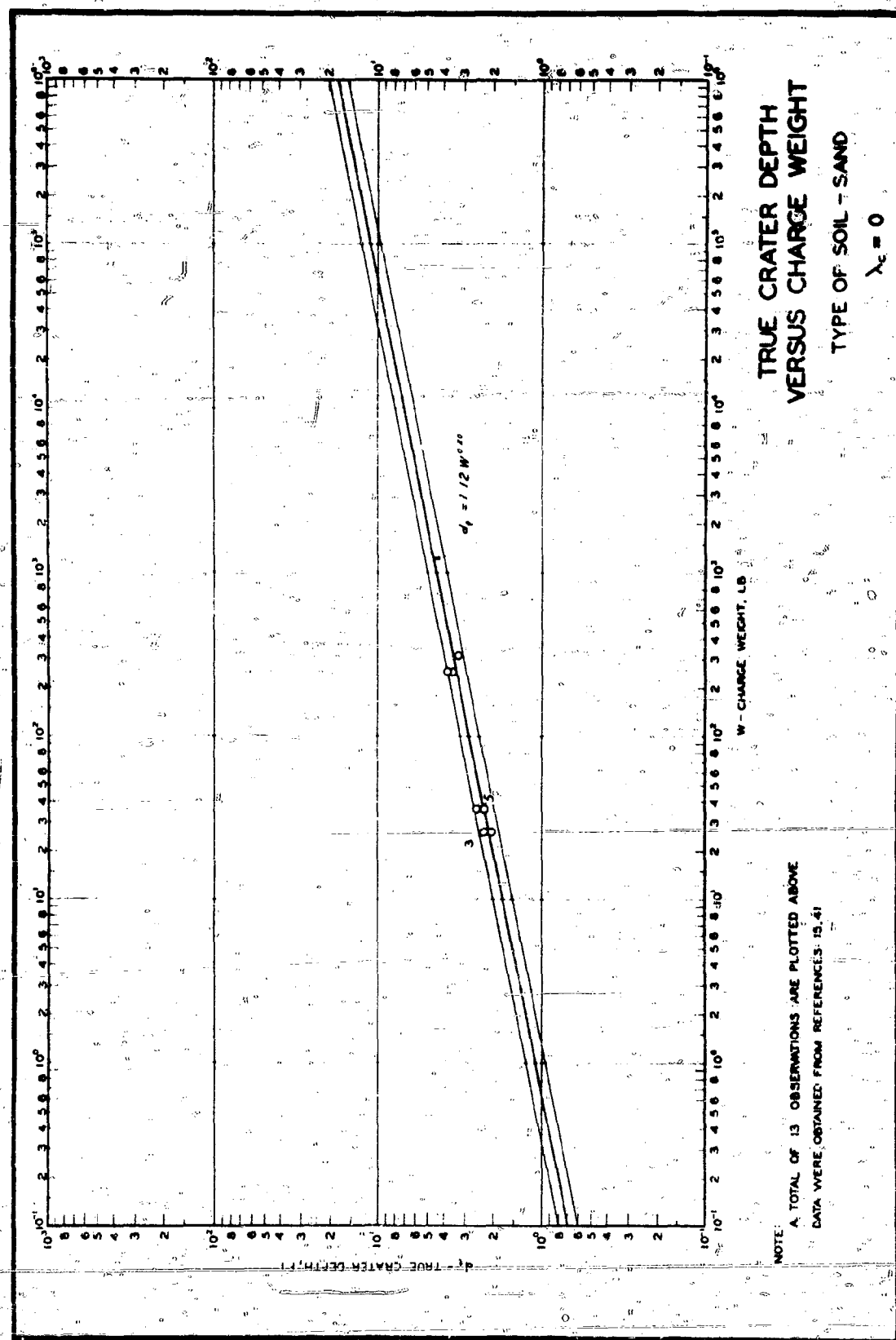
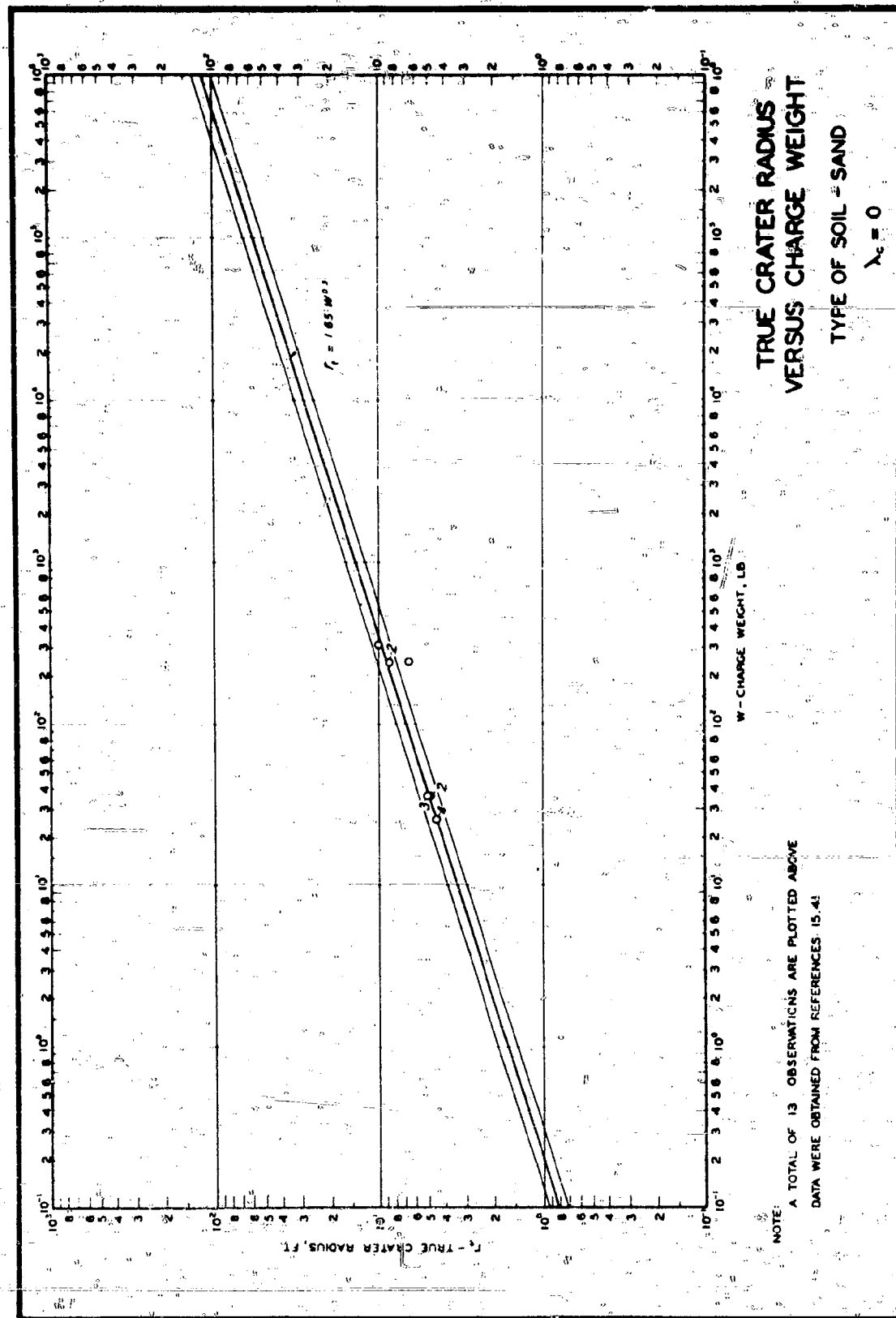
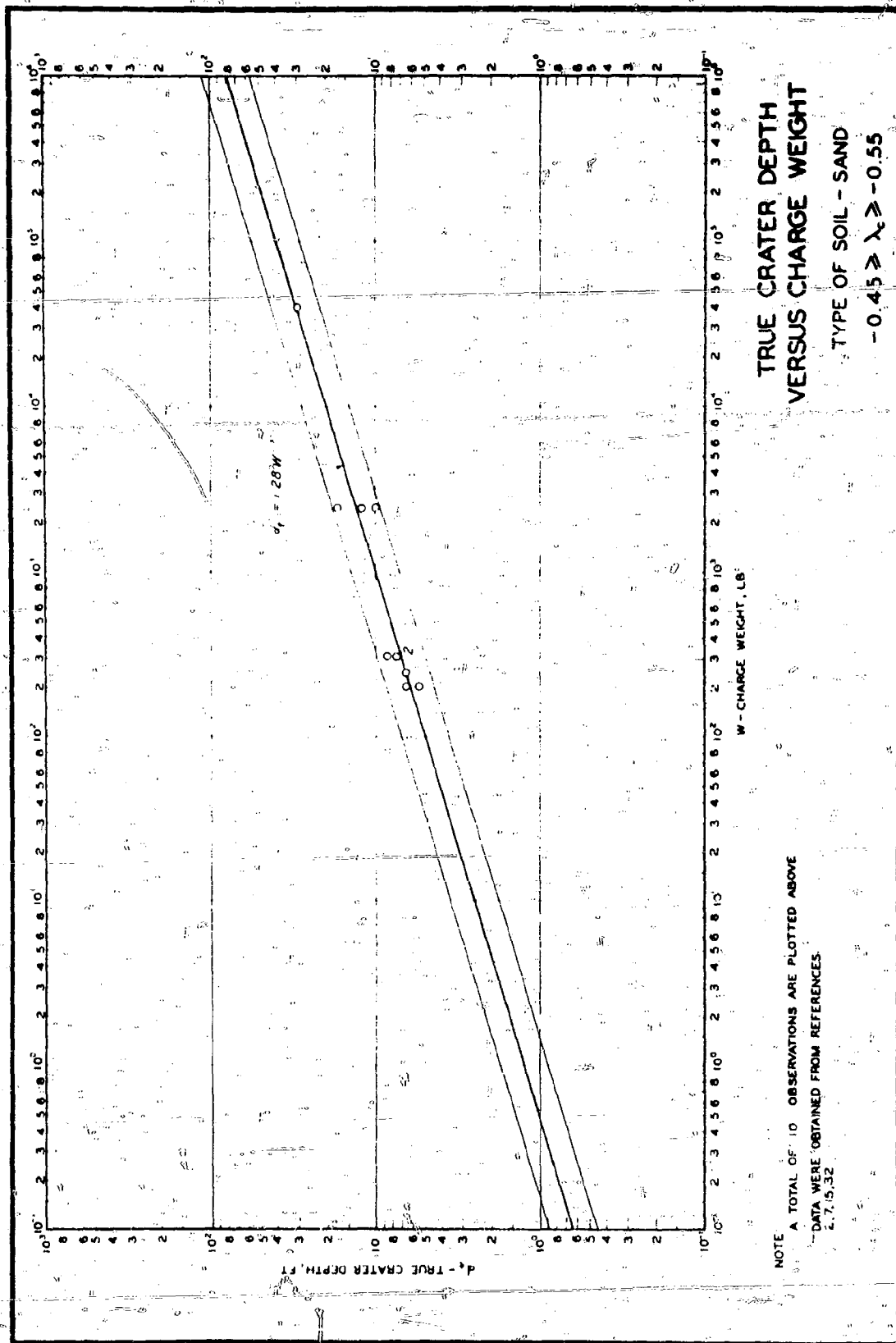
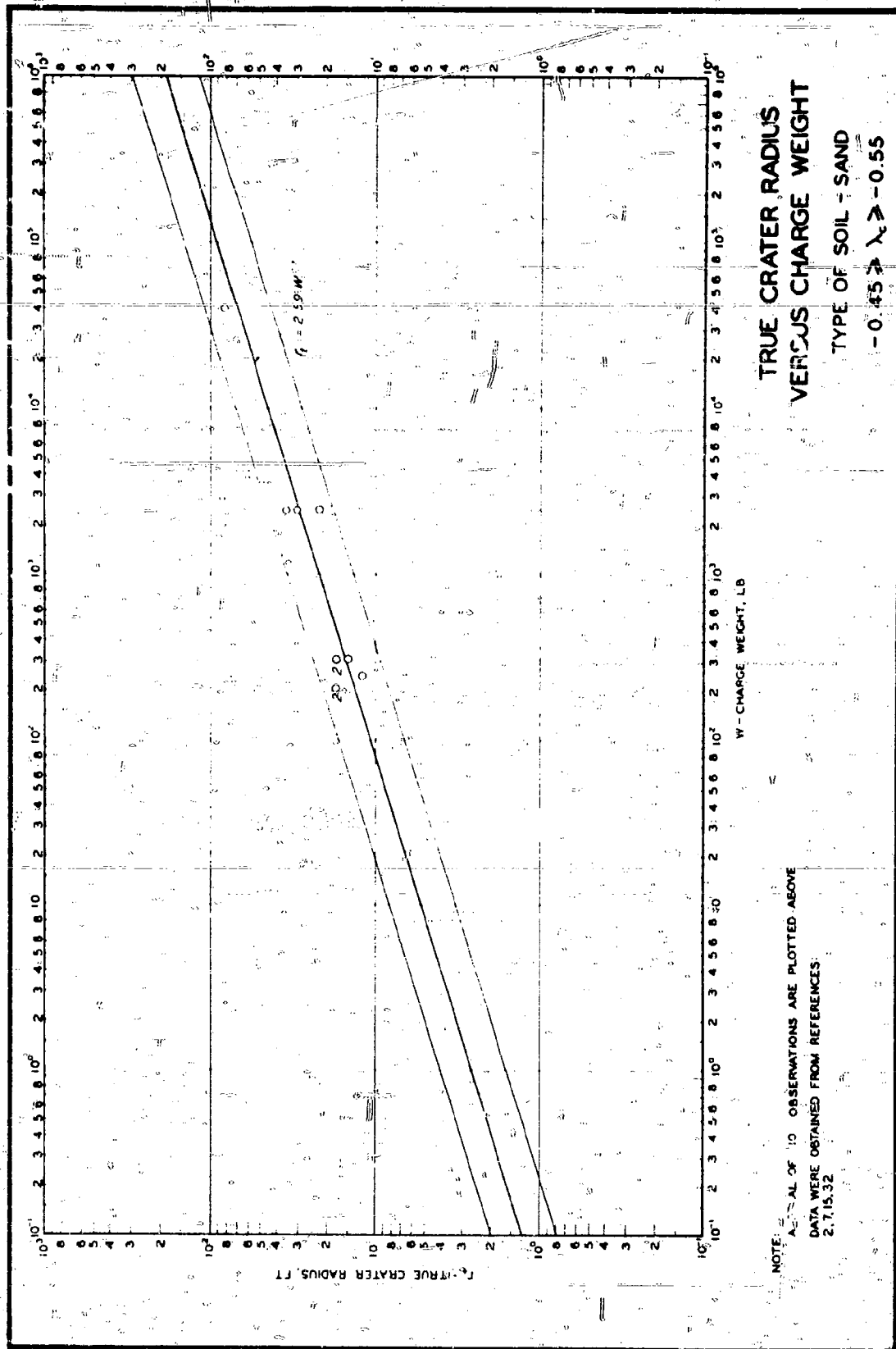
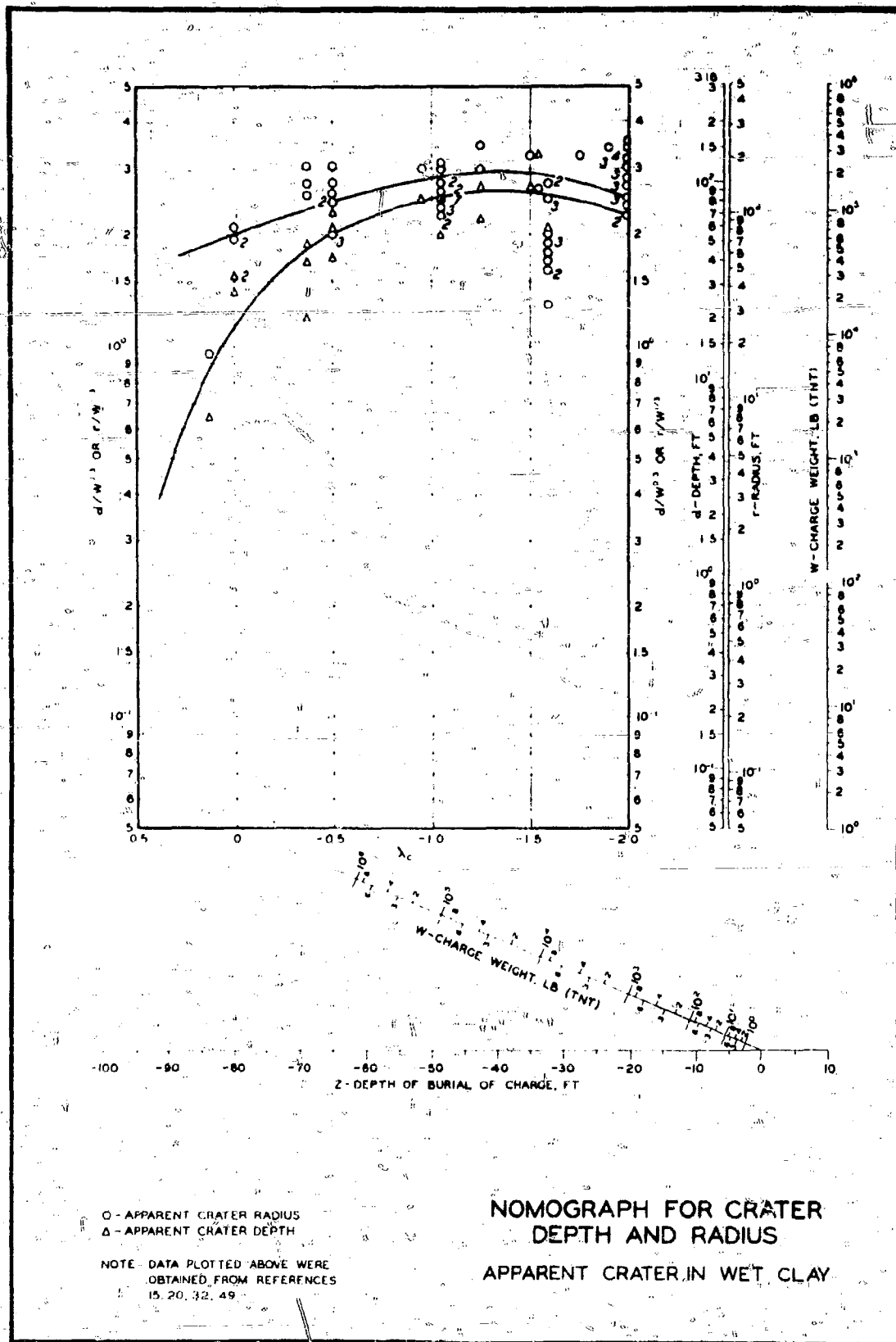


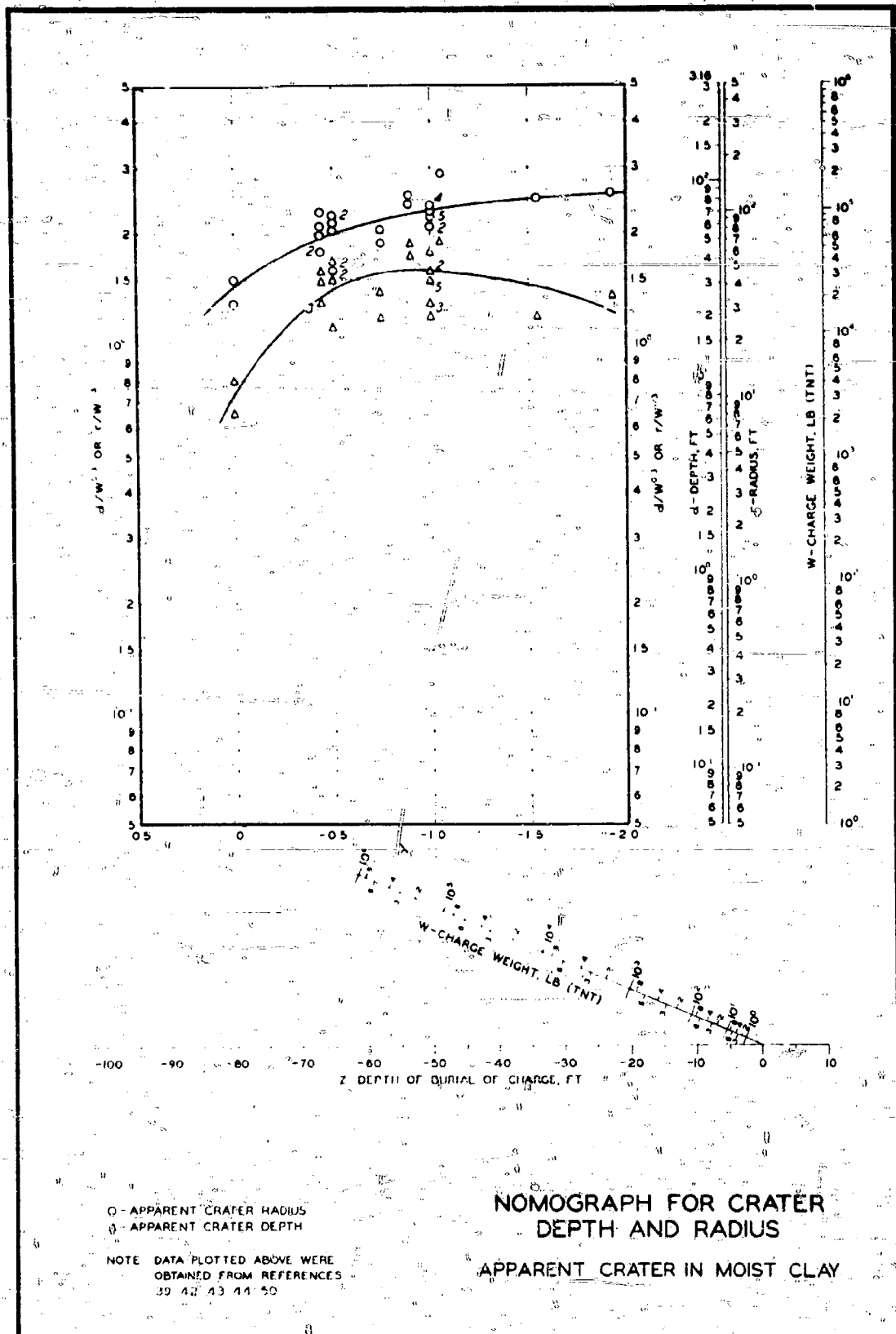
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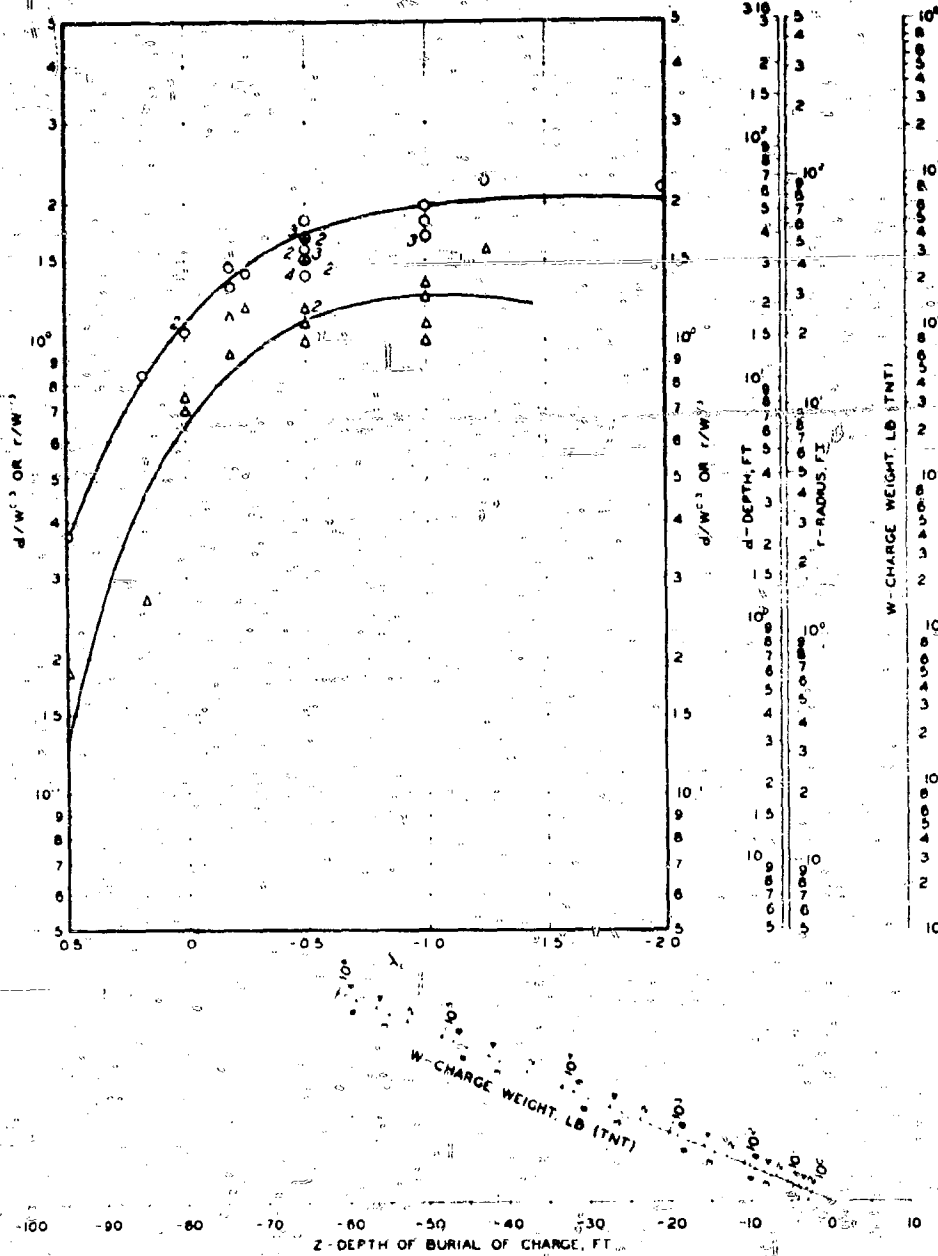








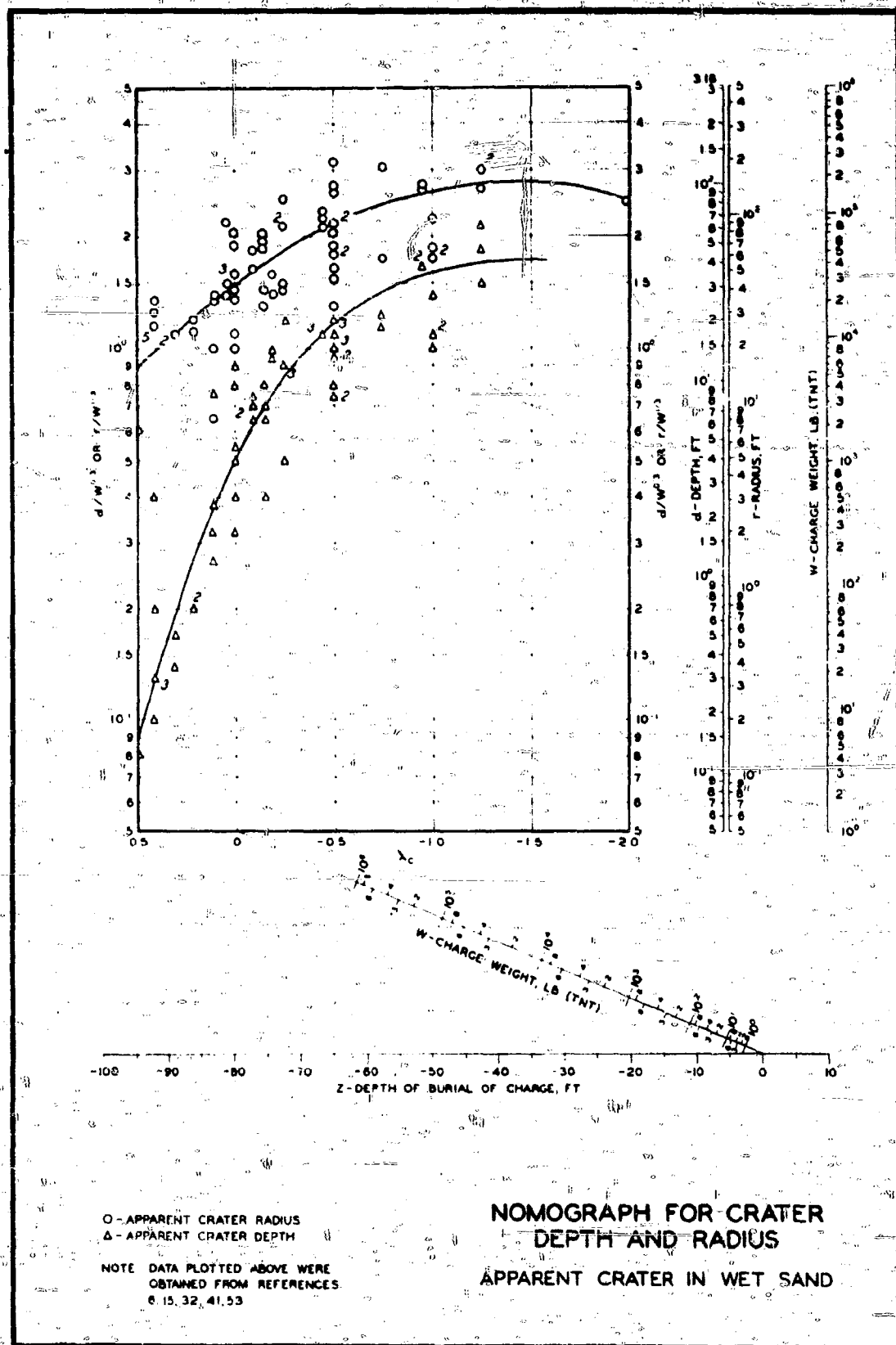


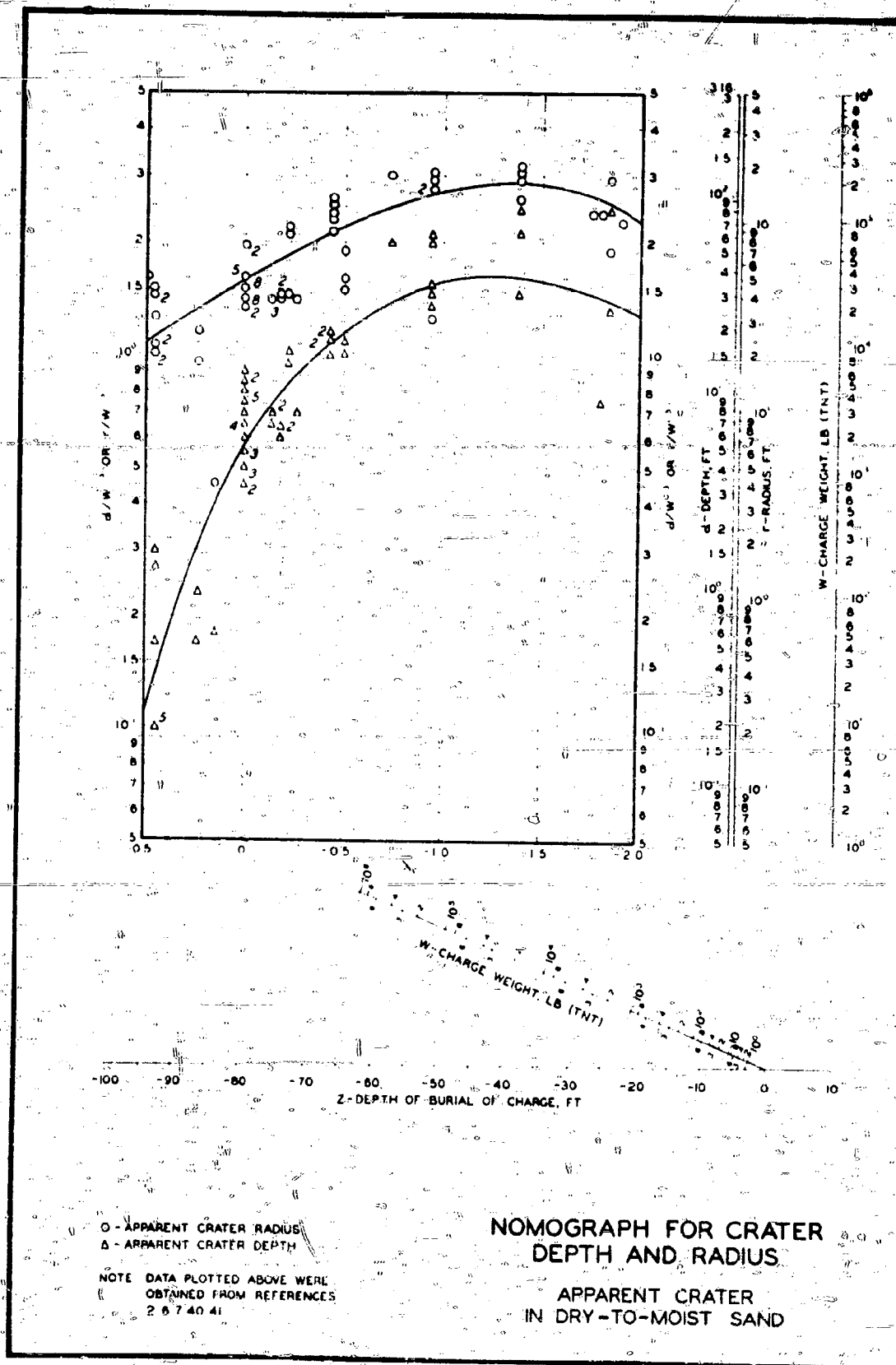


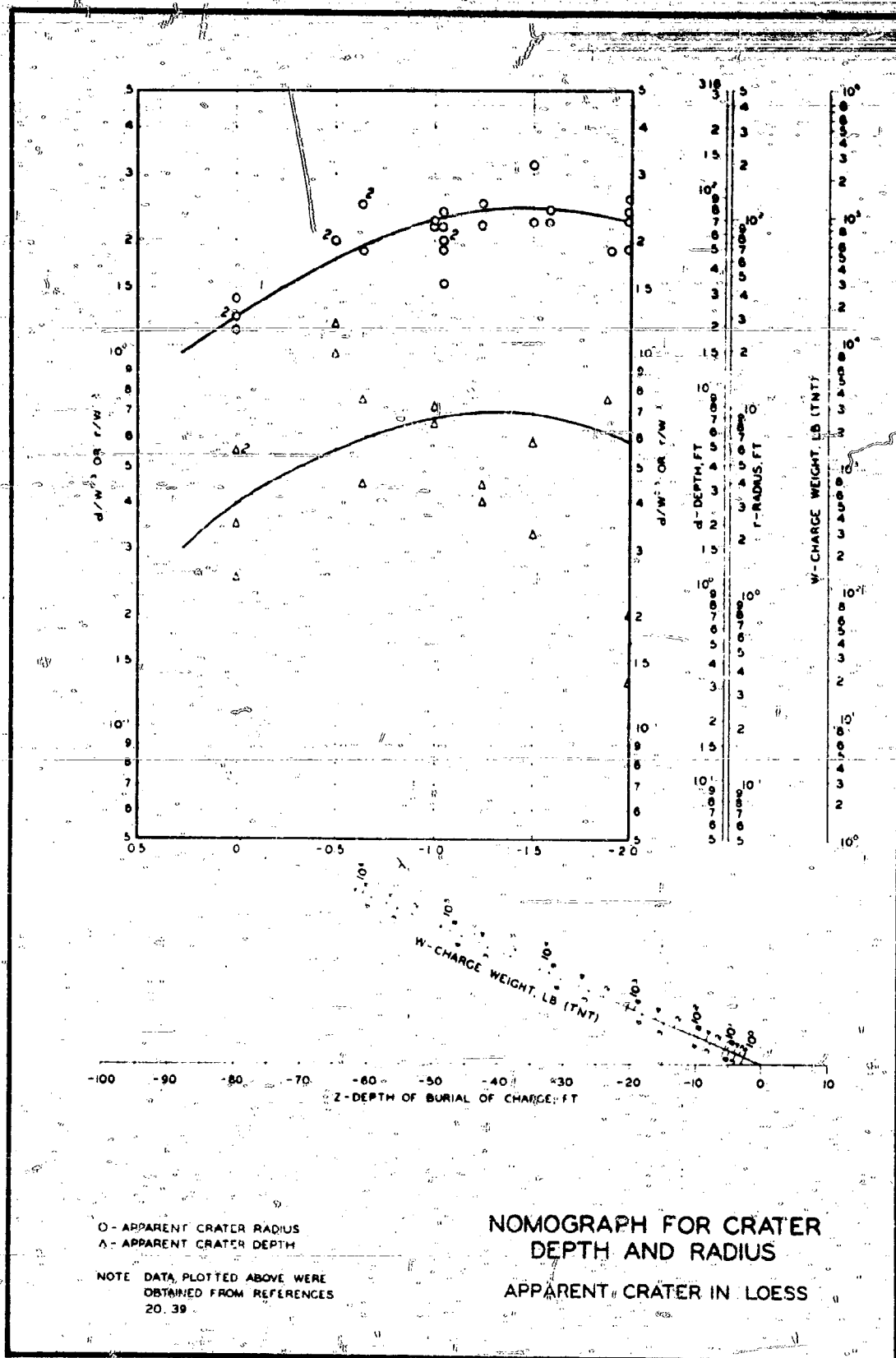
O - APPARENT CRATER RADIUS
 Δ - APPARENT CRATER DEPTH

NOTE DATA PLOTTED ABOVE WERE
 OBTAINED FROM REFERENCES
 15 32

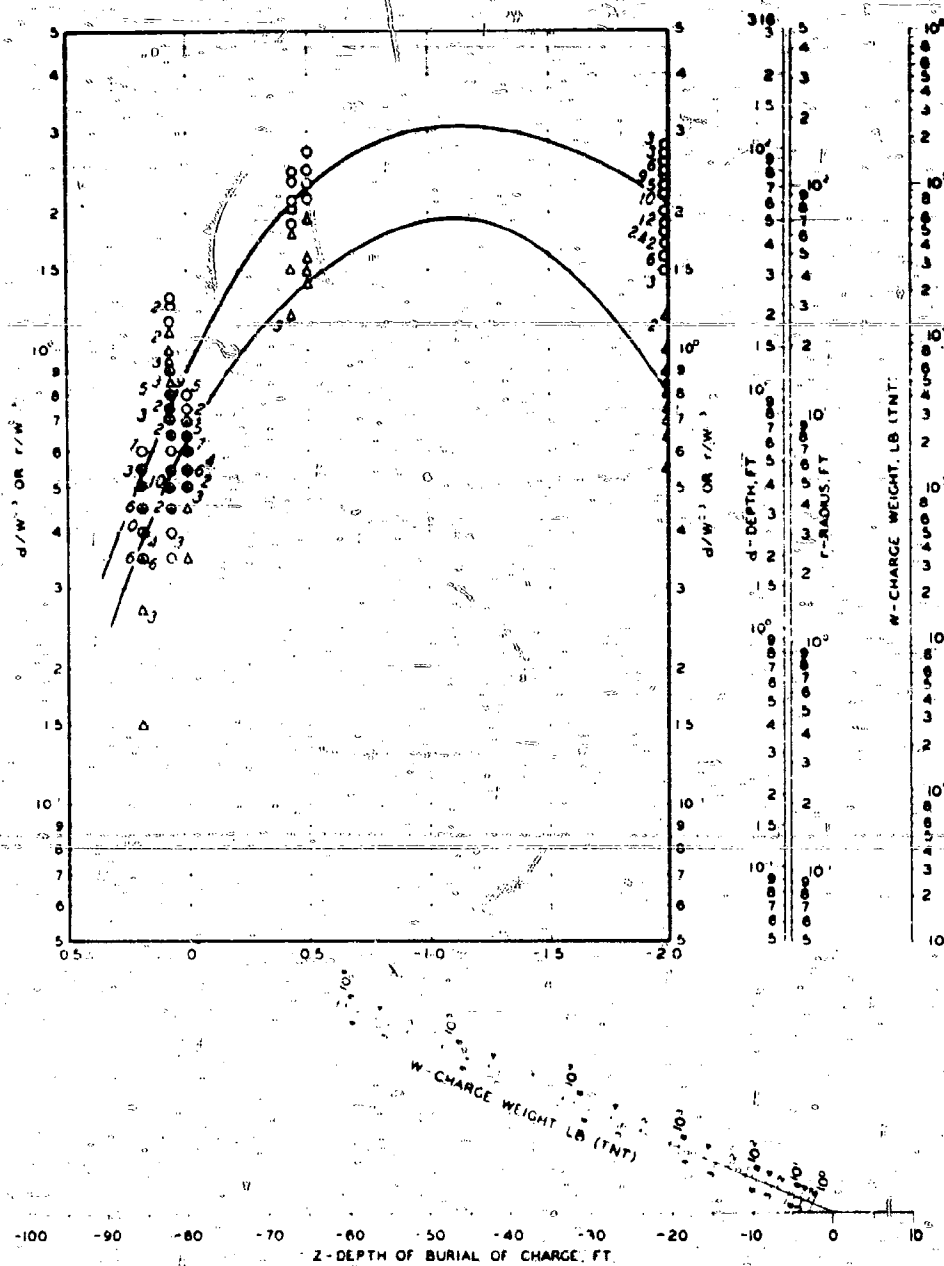
NOMOGRAPH FOR CRATER
 DEPTH AND RADIUS
 APPARENT CRATER IN DRY CLAY







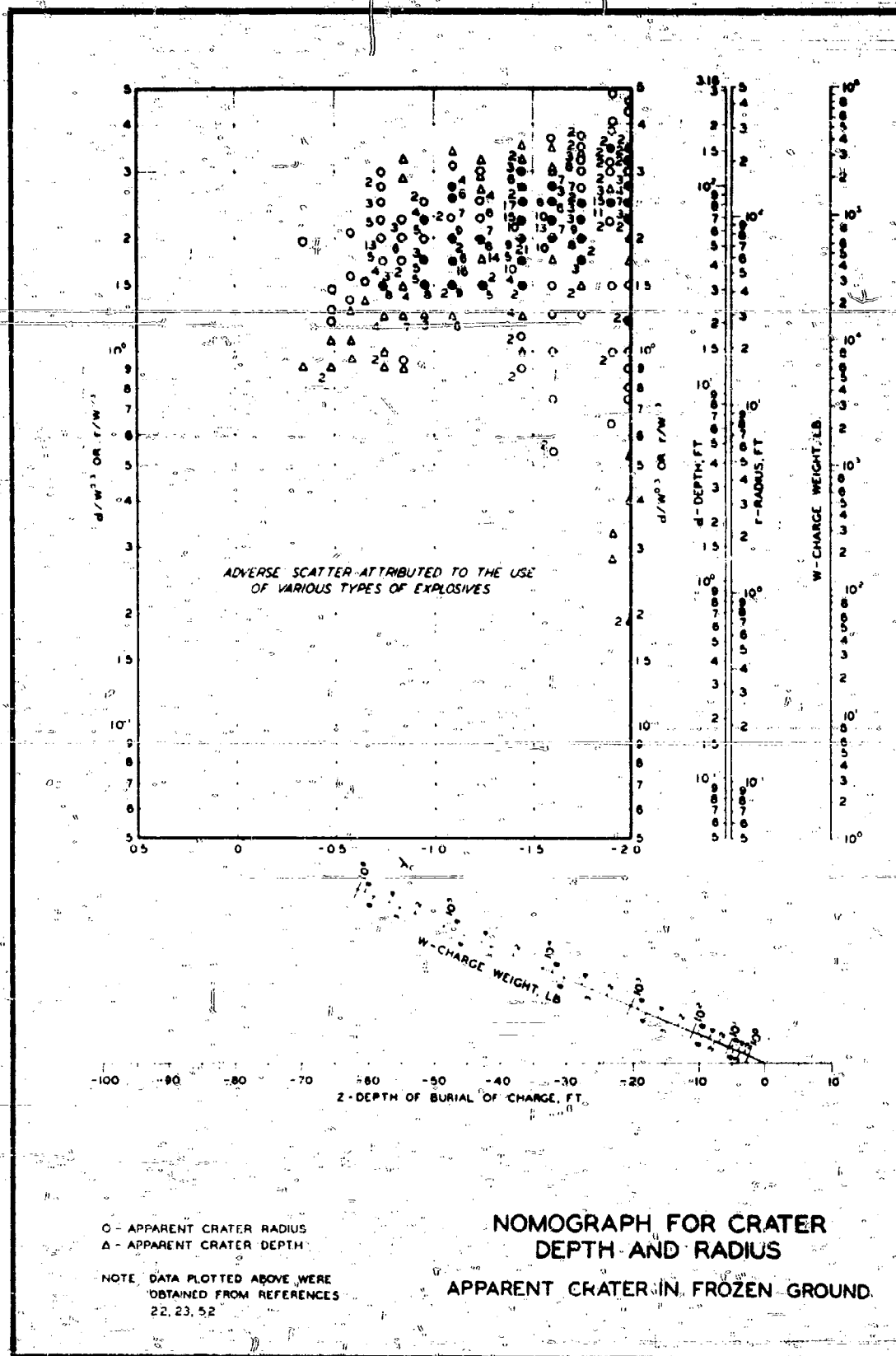
NOMOGRAPH FOR CRATER
DEPTH AND RADIUS
APPARENT CRATER IN LOESS

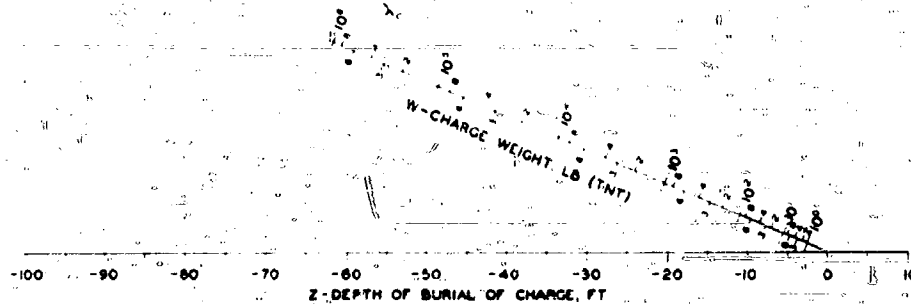
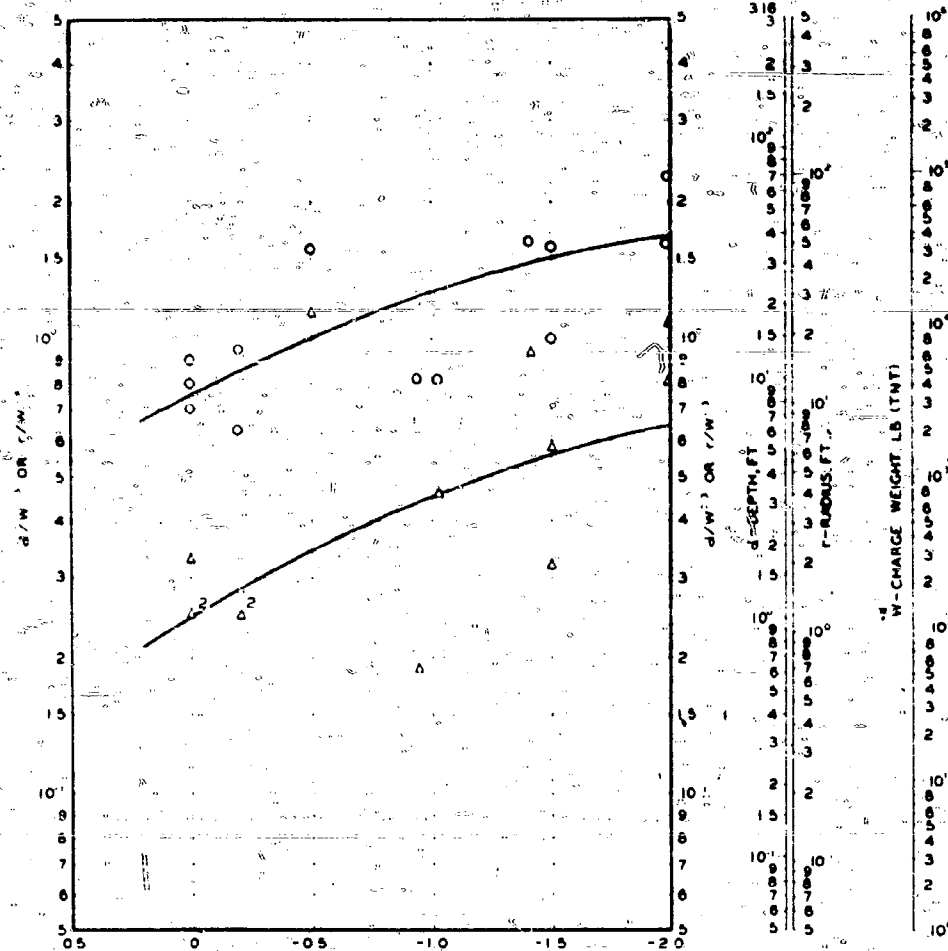


O - APPARENT CRATER RADIUS
 Δ - APPARENT CRATER DEPTH

NOTE: DATA PLOTTED ABOVE WERE
 OBTAINED FROM REFERENCES
 5.44, A-2

NOMOGRAPH FOR CRATER
 DEPTH AND RADIUS
 APPARENT CRATER IN SILT

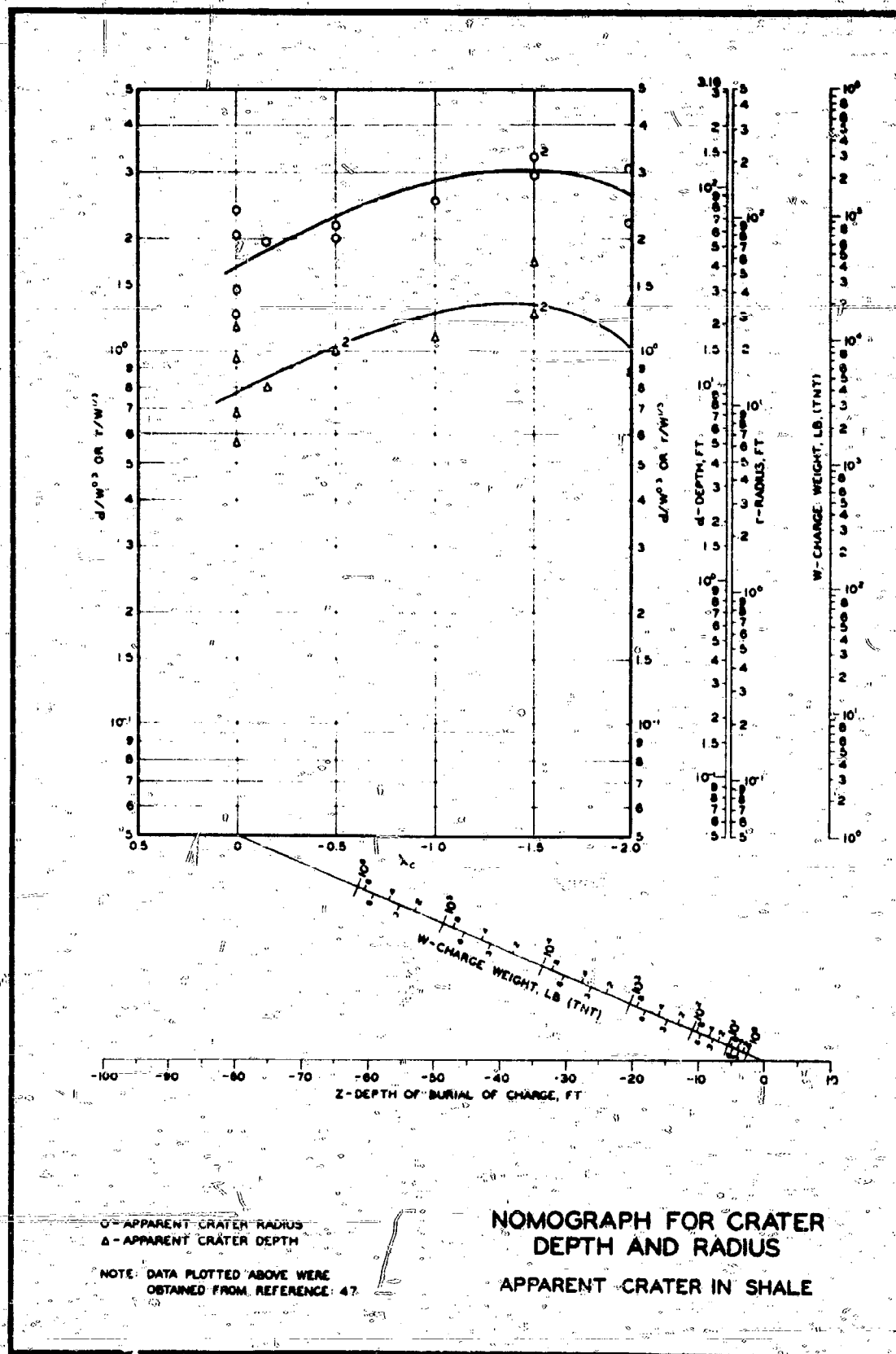


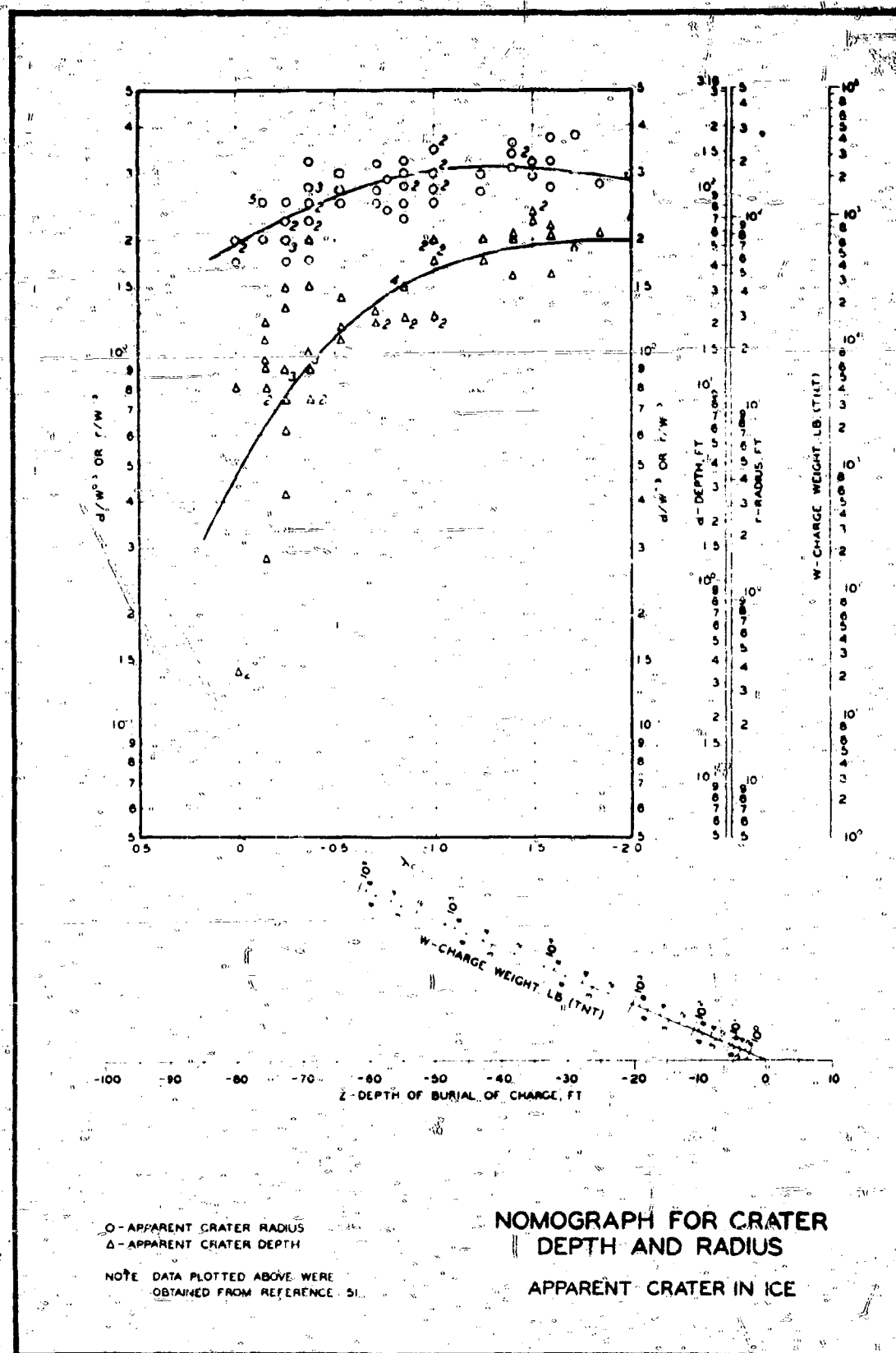


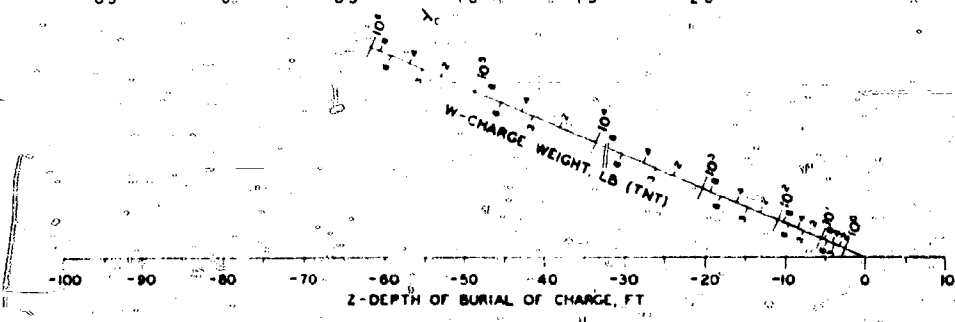
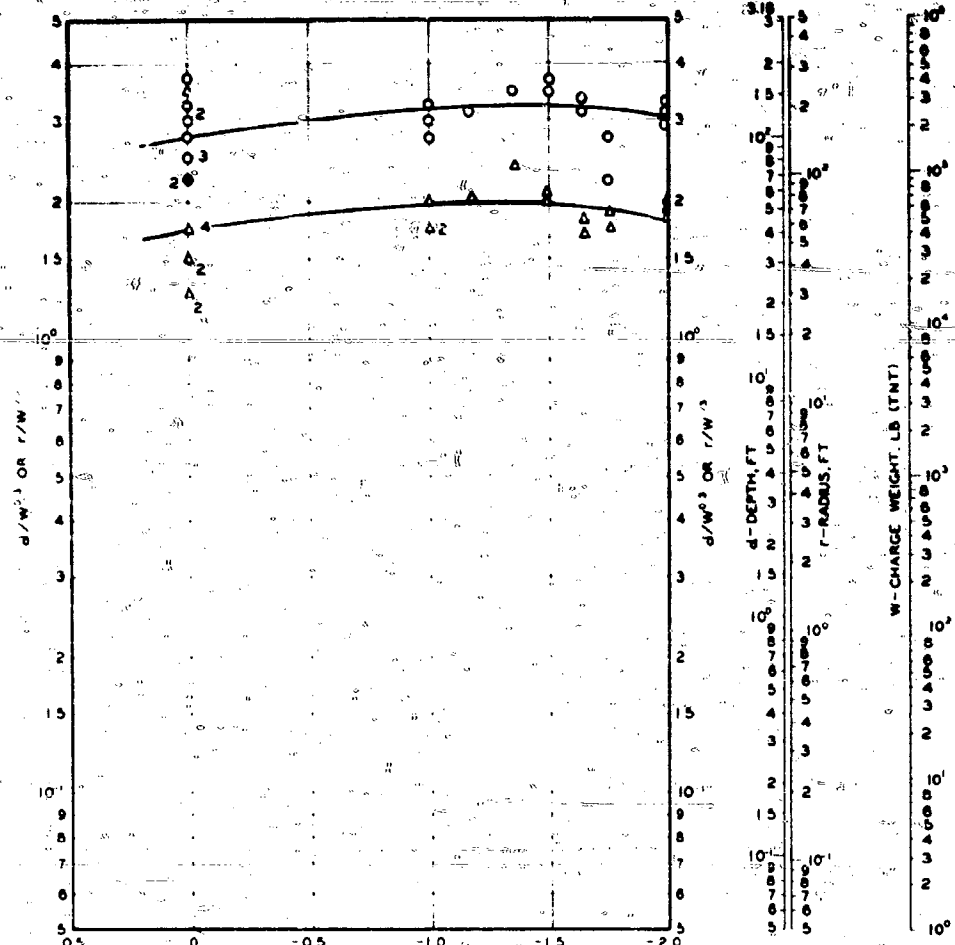
O - APPARENT CRATER RADIUS
 Δ - APPARENT CRATER DEPTH

NOTE DATA PLOTTED ABOVE WERE
 OBTAINED FROM REFERENCE 48

NOMOGRAPH FOR CRATER
 DEPTH AND RADIUS
 APPARENT CRATER IN BASALT



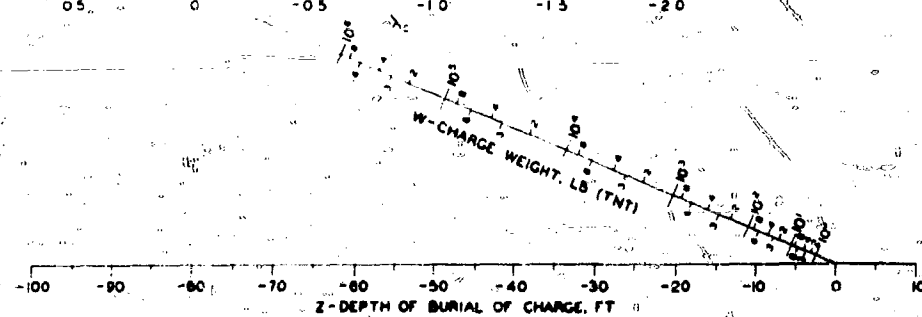
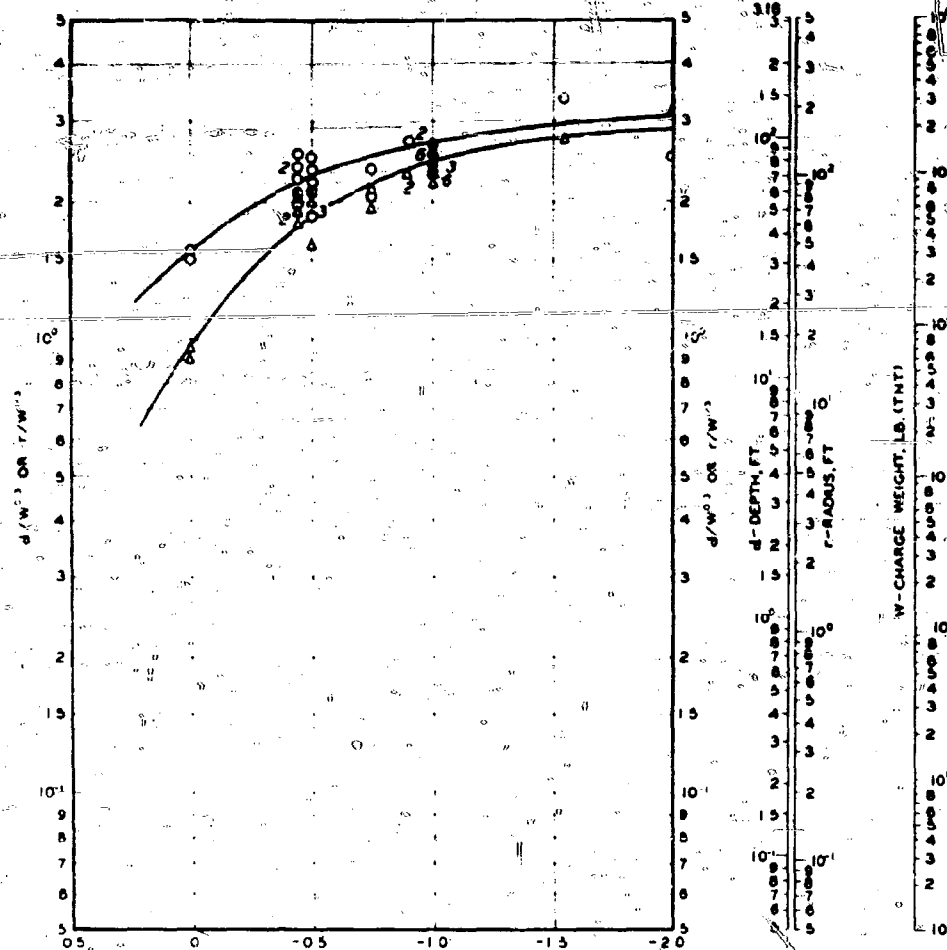




O - APPARENT CRATER RADIUS
 Δ - APPARENT CRATER DEPTH

NOTE DATA PLOTTED ABOVE WERE
 OBTAINED FROM REFERENCES
 19.38

NOMOGRAPH FOR CRATER
 DEPTH AND RADIUS
 APPARENT CRATER IN SNOW

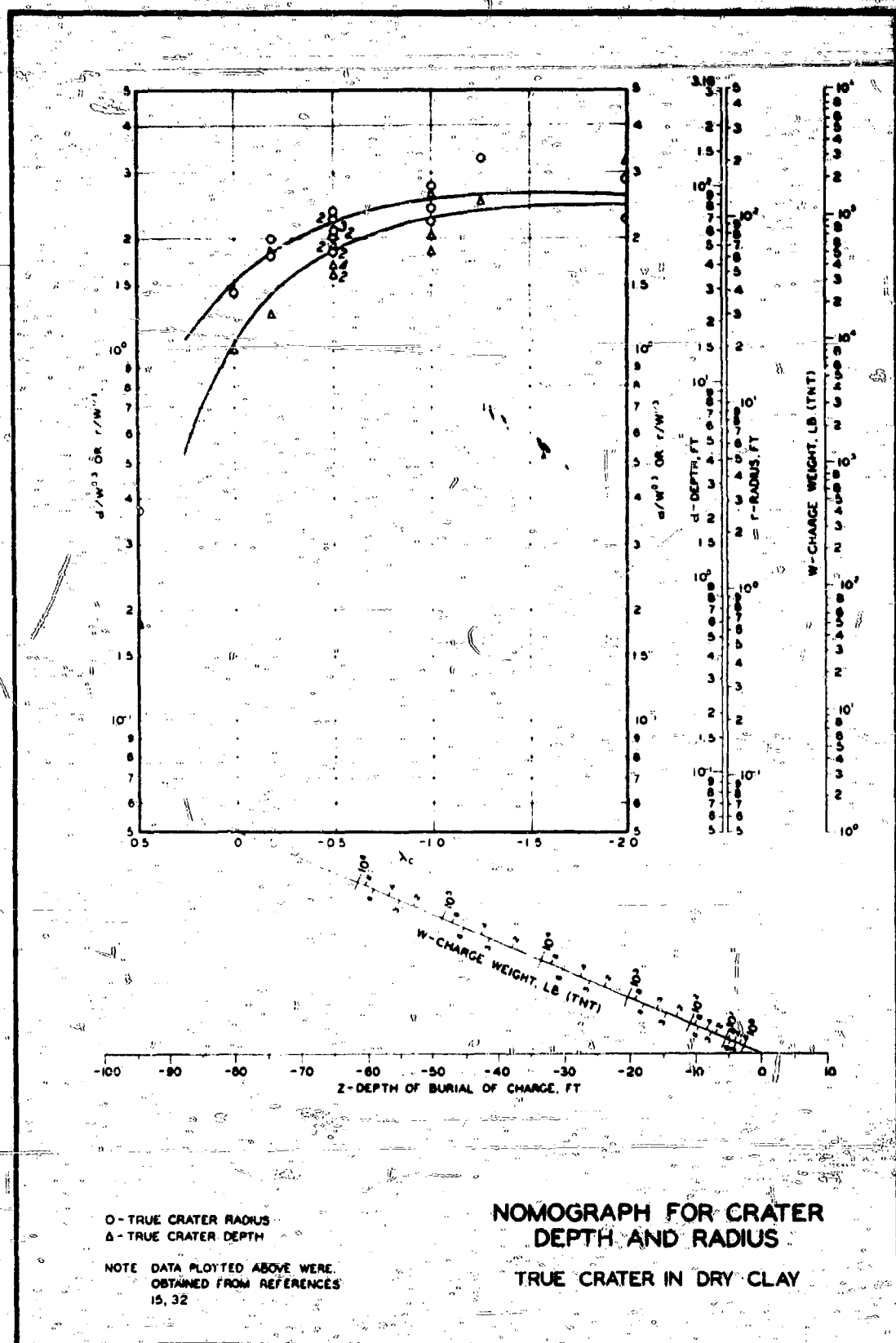


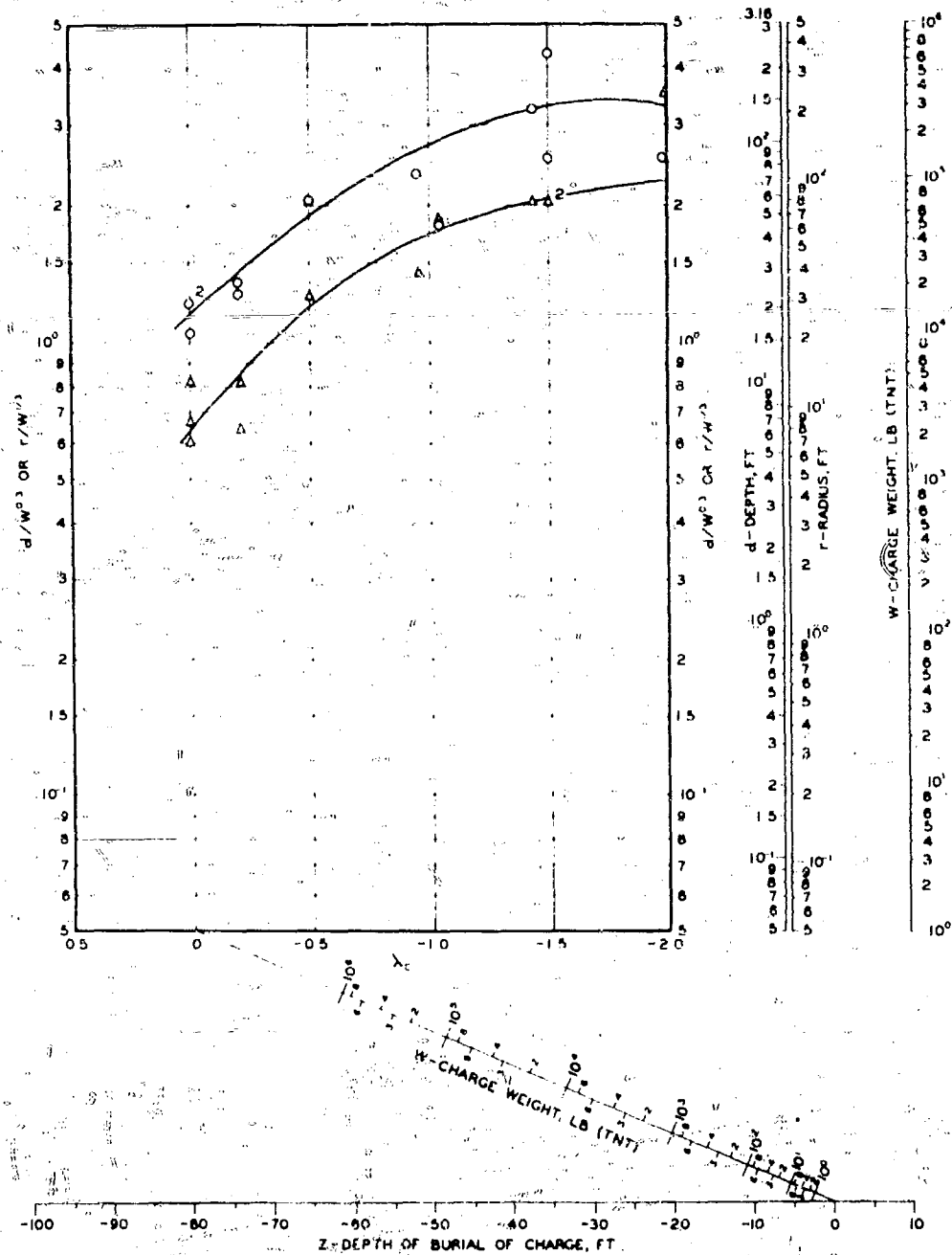
O - TRUE CRATER RADIUS
 Δ - TRUE CRATER DEPTH

NOTE DATA PLOTTED ABOVE WERE
 OBTAINED FROM REFERENCES
 39, 42, 43, 44, 50

NOMOGRAPH FOR CRATER DEPTH AND RADIUS

TRUE CRATER IN MOIST CLAY

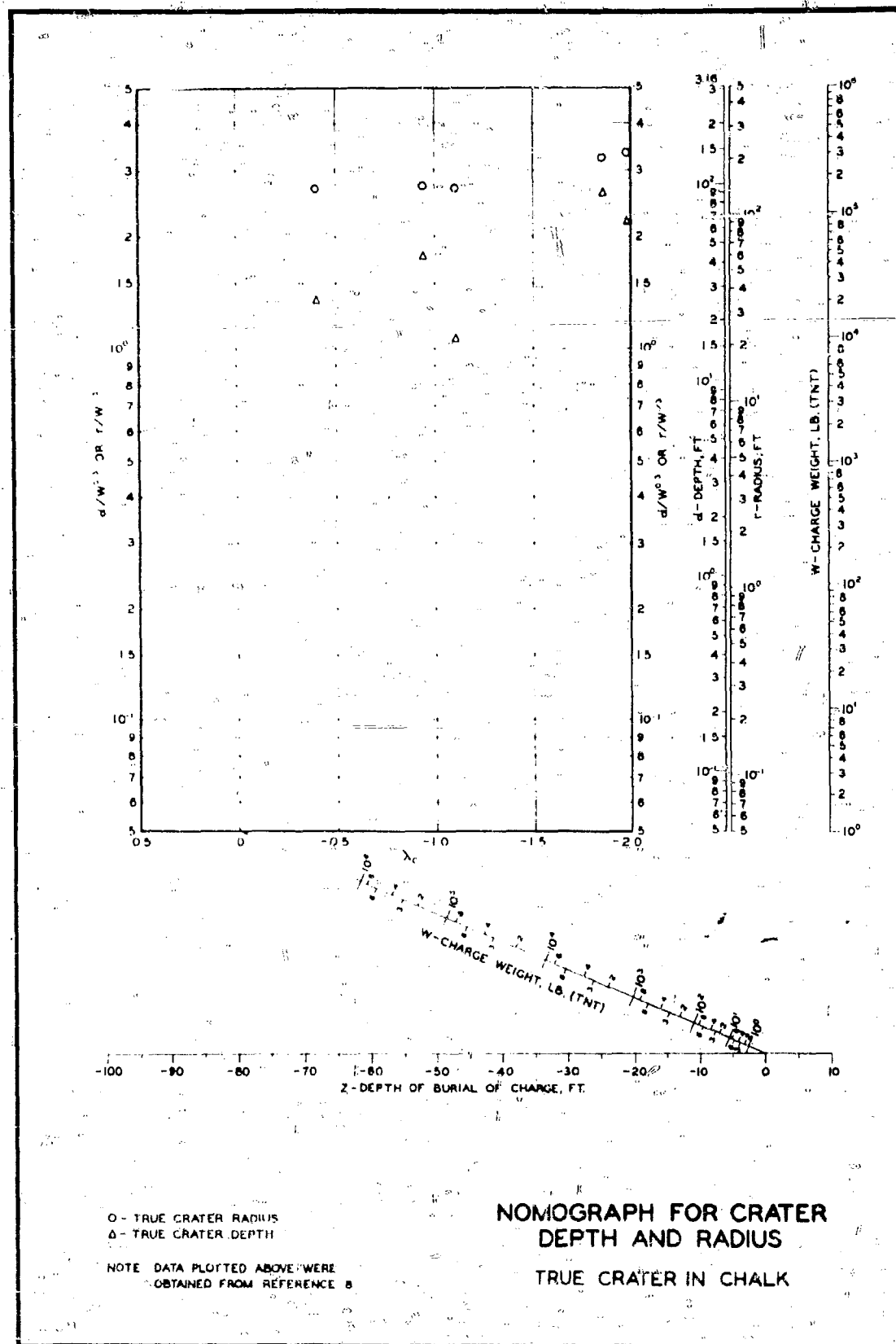


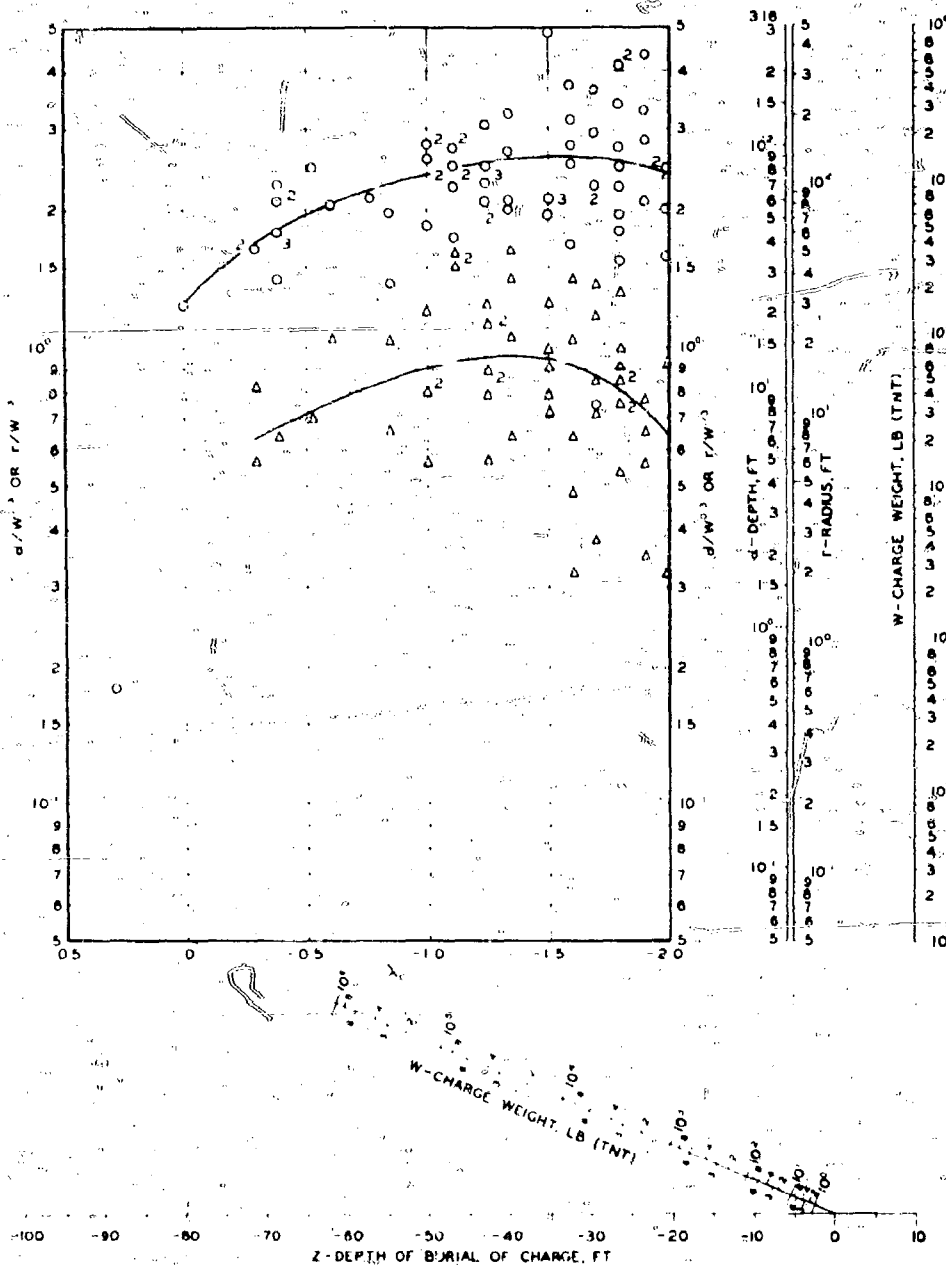


O - TRUE CRATER RADIUS
 Δ - TRUE CRATER DEPTH

NOTE DATA PLOTTED ABOVE WERE
 OBTAINED FROM REFERENCE 46

NOMOGRAPH FOR CRATER
 DEPTH AND RADIUS
 TRUE CRATER IN BASALT

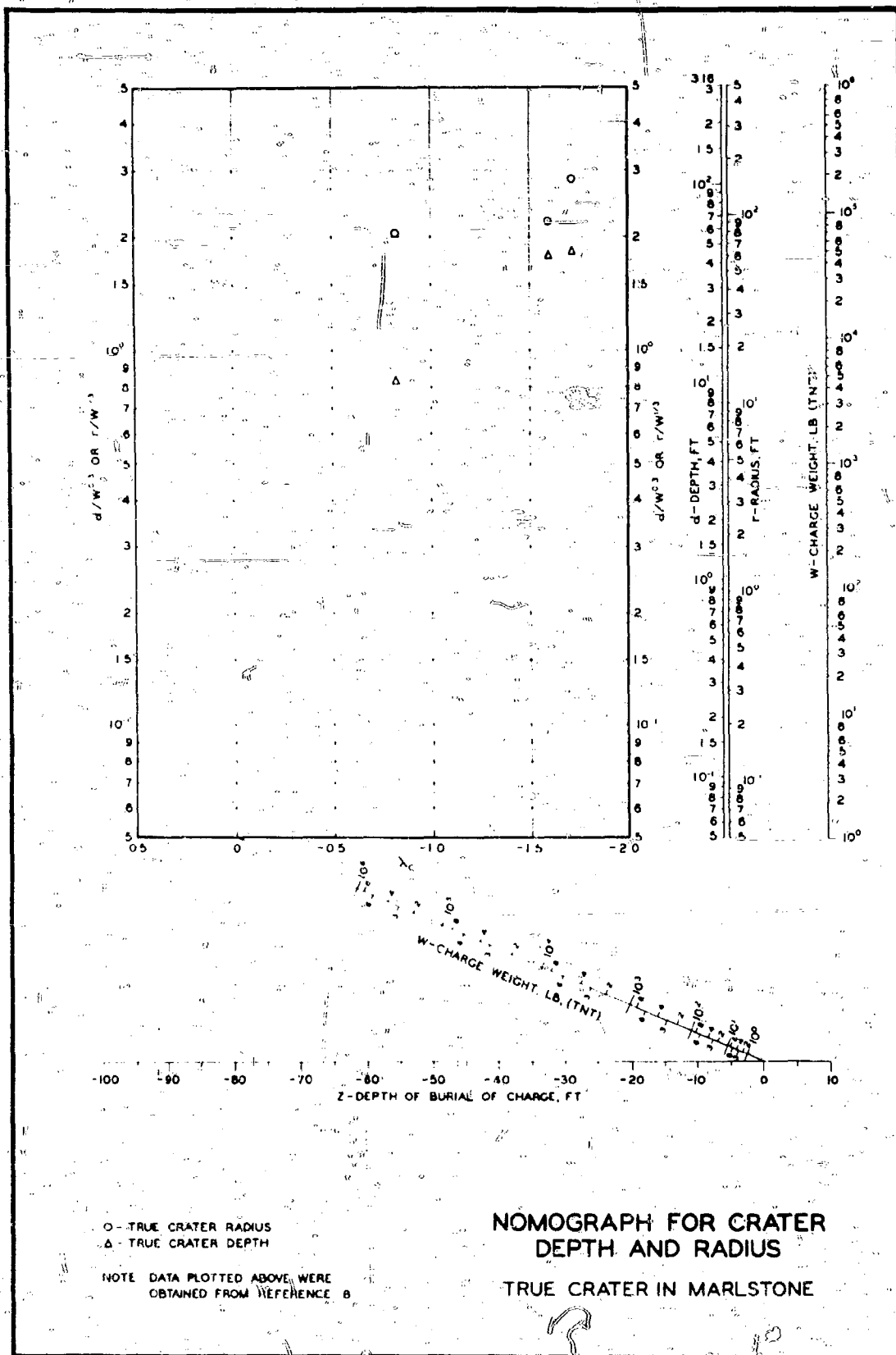


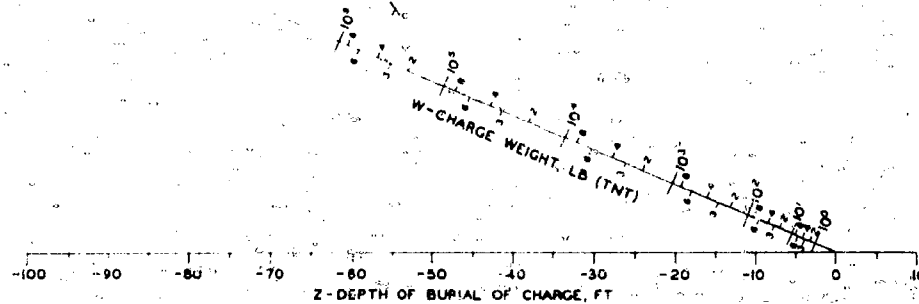
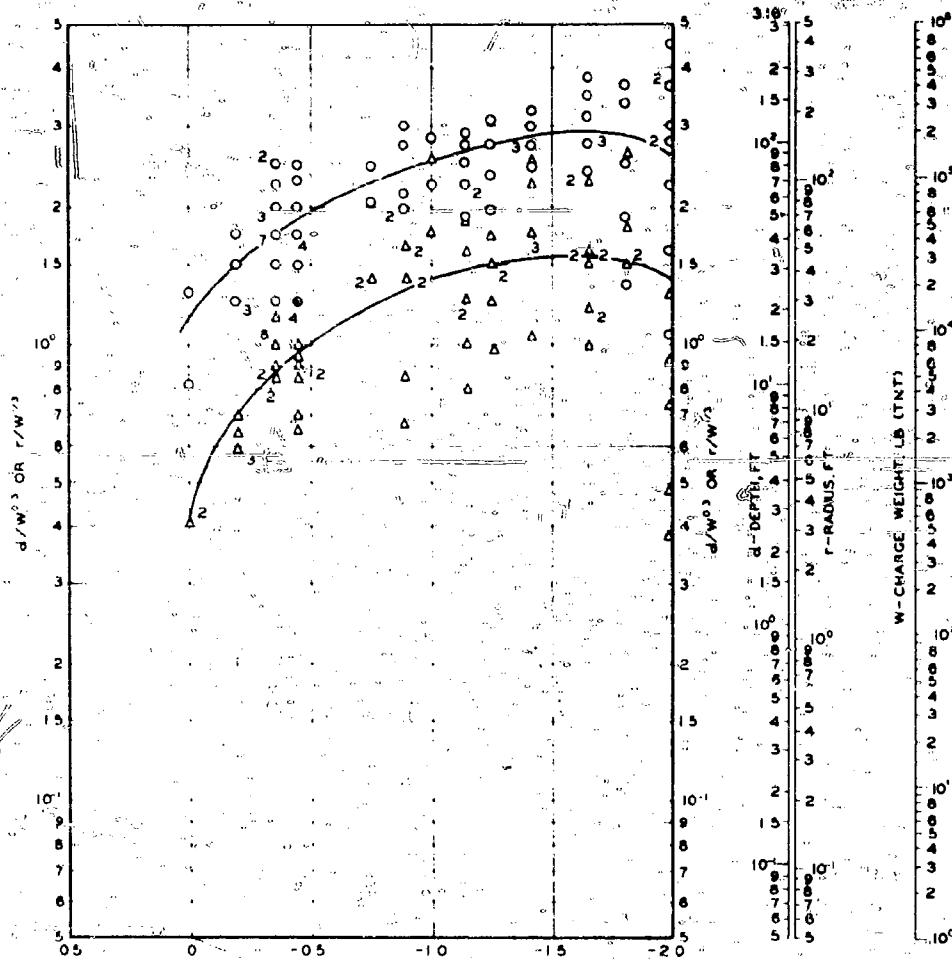


O - TRUE CRATER RADIUS
 Δ - TRUE CRATER DEPTH

NOTE DATA PLOTTED ABOVE WERE
 OBTAINED FROM REFERENCES
 4 5 6 7

NOMOGRAPH FOR CRATER
 DEPTH AND RADIUS
 TRUE CRATER IN GRANITE



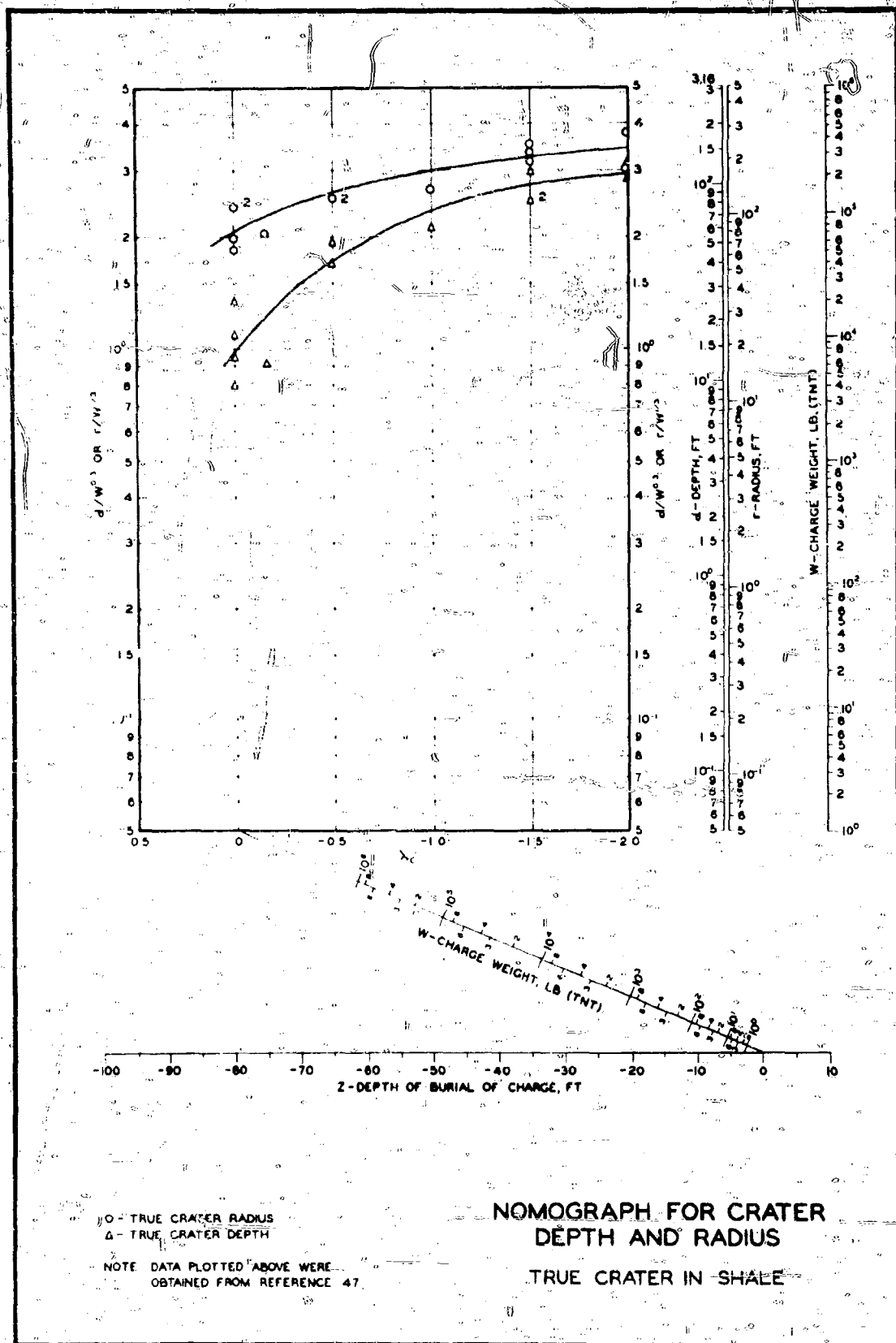


O - TRUE CRATER RADIUS
 Δ - TRUE CRATER DEPTH

NOTE DATA PLOTTED ABOVE WERE
 OBTAINED FROM REFERENCES
 4, 8, 14, 47, 48

NOMOGRAPH FOR CRATER DEPTH AND RADIUS

TRUE CRATER IN SANDSTONE



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